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WAVELET TRANSFORM FOR TIME-FREQUENCY
ANALYSIS OF VIBRATIONAL SIGNATURE
AND ITS APPLICATION

by

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ABSTRACT

Wavelet transform is applied to the analysis of vibration signatures in order to verify the ability of the detection of abnormal condition. It can well describe the dynamics of the signal's spectral composition of a non-stationary and stationary signal to be measured and presented in the form of 3-D time-frequency map. Although wavelet has been developed over about ten years in the mathematics and physics, its engineering applications is a first stage. The objective of this report outlines the definition of the wavelet transform and is to discuss the properties of the wavelet transform as new tool for the vibration analysis, and then demonstrates how it may be applied to the machinery condition monitoring.

I. INTRODUCTION

Wavelets are a very popular topic of the signal processing and applied mathematics. In the last ten years, an interest in them has grown at an fast rate in signal and numerical analysis [Beylkin, Coifman and Rokhlin, 1991, Heil, 1990 and Resnikoff and Burrus, 1990]. Wavelet analysis appears to new subject for the time-frequency analysis of the vibrational signatures. Traditional spectral analysis provides spectral values which are independent of time. It is assumed to be ergodic and stationary signal with

time. However the signal associated with most vibrational phenomena are in general time varying, which means that their characteristics change with time and they have various features in different time frames. For example, the vibration during the start-up of an engine or pump is non-stationary, the sound pressure generated from speaker is nonstationary, and so on. In case of the signal containing some transient or nonstationary conditions, the traditional approach in signal analysis fails to describe the dynamics of the signal's frequency components changes. Changes in the condition of a component such as a gear can be expected to cause some change in the vibration generated by mechanical system. Very little damage detection can be performed using the vibration signal directly from the system because the small changes generated by early damage may be masked by the normal vibration of the system.

Two methods of signal analysis for nonstationary application are commonly used in time-frequency domain. The windowed Fourier transform, otherwise so called short time Fourier transform(STFT), has a short time window of a fixed size centered at time t as figure 1(a). The windowed Fourier transform is given as follows

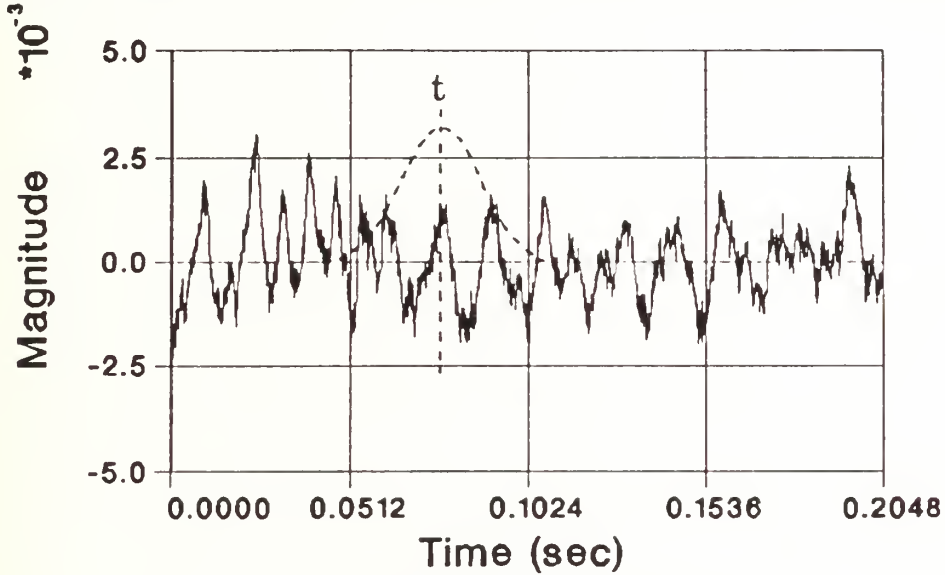
$$F(\omega, t) = \int g(\tau - t) e^{-i\omega\tau} s(\tau) d\tau \quad (1)$$

where $F(\omega, t)$ is the windowed Fourier transform, $g(t)$ window function and $s(t)$ time signal. The range of integration is from $-\infty$ to ∞ . If the length of the window is time duration T , the resolution of time frequency domain depends on T . Its frequency bandwidth or frequency resolution is approximately $1/T$. Therefore this method have the limitation of resolution in both time and frequency domain simultaneously.

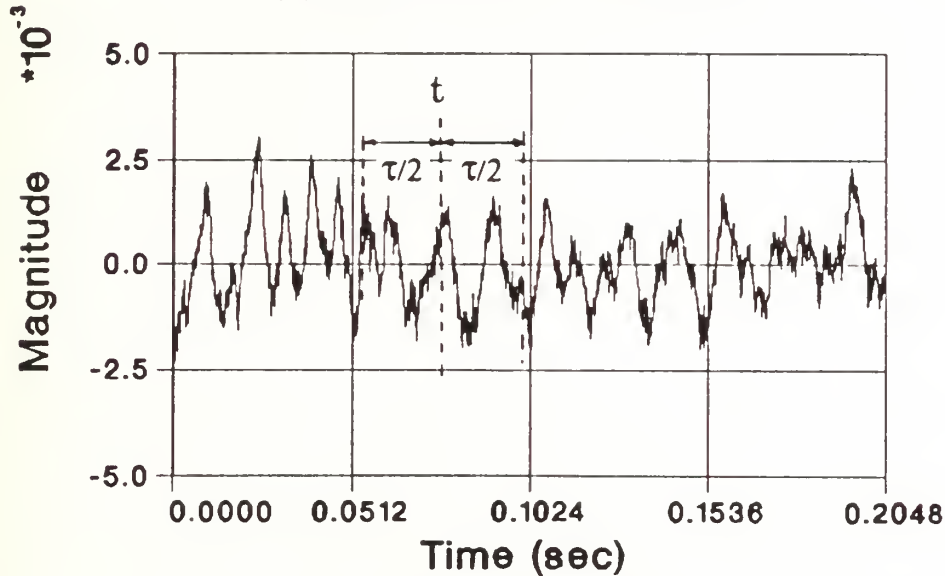
The second method, often called Wigner distribution method, is based on the instantaneous power spectra defined as following equation (2)

$$w(\omega, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} s(t - \tau/2) s(t + \tau/2) e^{-i\omega\tau} d\tau \quad (2)$$

where $w(\omega, t)$ is Wigner distribution function. Equation (2) is called the Wigner distribution of $s(t)$ in figure 1(b). We discussed well at references [Jeon and Shin (1993) and Shin, Jeon and Spooner (1993)] about the characteristics of Wigner-Ville distribution. For a nonstationary signal analysis, spectrogram is commonly used, which is based on the assumption that it is a collection of a short duration stationary signal.



(a) Windowed Fourier transform



(b) Wigner distribution

Figure 1. Calculation of the windowed Fourier transform and instantaneous spectral density(Wigner distribution) of a vibration signal.

A major drawback of this approach is that the frequency resolution is directly affected by the duration of short stationary time, which subsequently determines the time resolution. The frequency and time resolution of the Wigner distribution are not determined by the short duration but rather determined by the selection of desired resolution of the signal itself, but may not be appropriate for signals containing patterns at both large and very small scales.

The windowed Fourier transform is well portray the characteristics of signals in which all of the patterns appear at approximately the same scale, but may not be appropriate for signals containing patterns at both large and small scales because of the time fixed window size. The multifrequency channel decomposition, which are an intermediate between a time and a Fourier representation, have found many applications in signal and image processing [Mallat, 1989]. Much recent research has been focused on this domain with the modeling of a new decomposition called the wavelet transform, which is presented signal by summation of family of functions which are the dilations and translations of a unique function called a wavelet. Instead of portraying a signal into harmonic functions ($e^{i\omega t}$ in Fourier transform), the signal is presented into a series of orthogonal basis functions of finite length. Each wavelet is located at a different position on the time axis. At the finest scale, wavelets may be very short indeed; at a coarse scale, they may be very long. Alternatively very small disturbances in a record of machinery vibration can be easily characterized from a wavelet 3-D or 2-D map in which the mean-square value of the time record is shown over wavelet scale and position.

One important property of a wavelet transform is its ability to characterize easily the local regularity of a function. Simply by a change of the scale parameter(dilation) in the wavelet transform, many scales of local structure can be described by a distribution in the time-scale plane. Wang and McFadden (1993) introduced the advantage for examining the vibration signal generated by a gear and D. E. Newland (1993) well investigated the properties of the wavelet as a new tool for the analysis of vibration records.

This report outlines the definition of the wavelet transform, compare with the advantages and the disadvantages of wavelet and pseudo Wigner-Ville distribution in time-frequency domain analysis, and then demonstrates how it may be applied to analysis of the vibration signals for the machinery condition monitoring.

II. DEFINITION OF WAVELET TRANSFORM

To overcome the limitation of the fixed resolution of the windowed Fourier transform in the time and frequency domains by decomposing the signal $s(t)$ into a family of functions which are the translation and dilation of an unique function $\psi(t)$, defined the continuous wavelet transform as

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \overline{\psi\left(\frac{t-b}{a}\right)} s(t) dt \quad (3)$$

where $W(a,b)$ is wavelet transform, ψ is an analyzing wavelet, a represents a time dilation, b a time translation, and bar for complex conjugate. The normalization factor $1/\sqrt{a}$ is perhaps most effectively visualized as endowing $|W(a,b)|^2$ with unit of power/Hertz [Shensa, 1992].

We consider the space $L^2(\mathbf{R})$ of measurable function ψ , defined on the real line \mathbf{R} ($\mathbf{R} := (-\infty, \infty)$), certain weak 'admissibility' conditions are usually required on $\psi(t)$ [Shensa, 1992];

$$\int_{-\infty}^{\infty} \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty \quad (4)$$

where $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$. They ensure that the transformation is a bounded invertible operator in appropriate space [Daubechies, 1988]. If $\hat{\psi}(\omega)$ is differentiable, then it suffices that ψ be zero mean, that is,

$$\int_{-\infty}^{\infty} \psi(t) dt = 0 \quad (5)$$

for equation (4) to be satisfied. In particular, since the local average values of every function in $L^2(\mathbf{R})$ must 'decay' to zero at $\pm\infty$, the sinusoidal(wave) functions $e^{i\omega t}$ (basis of Fourier transform) do not belong to $L^2(\mathbf{R})$. Fourier series representation of any functions is in $L^2(0,2\pi)$. In fact, if it looks for

wavelets that generate $L^2(\mathbf{R})$, these wavelets should decay to zero at $\pm\infty$; and for all practical purposes, the decay should be very fast [Chui, 1992].

In signal processing, the significance of equation (3) is well understood by comparing it to the windowed Fourier transform (or short-time Fourier transform):

$$F(\omega, b) = \int_{-\infty}^{\infty} g(t - b) e^{-i\omega t} s(t) dt. \quad (6)$$

Thus, to obtain $F(\omega, b)$, one multiplies the signal by an appropriate window $g(t)$ (such as Gaussian) centered at time b and then takes the Fourier transform. In mathematical forms, equation (6) is an expansion of the signal in terms of family of functions $g(t-b)e^{i\omega t}$, which are generated from a single function $g(t)$ through translations b in time and translations ω in frequency. In contrast, the wavelet transform of equation (3) is an expansion in function $\psi((t - b)/a)$ generated by translation b and dilation a in time. Thus, the continuous wavelet transform is similar to windowed Fourier transform with a different window size for each frequency. The important facts of this is that, while the basis functions in equation (6) have the same time and frequency resolution at all points of the transform plane, those of wavelet transform have the time resolution which decrease with increasing a and the frequency resolution which increase with decreasing a width adapted to their frequency components: at high frequency ψ are very narrow, while at low frequency ψ are much broader. As a results, the wavelet transform is better than the windowed Fourier transform to analyze on very small disturbance, i.e., high frequency phenomena. This property can be a best advantage in signal processing since high frequency characteristics are generally highly localized in time whereas slowly varying signals require good low frequency resolution [Shensa, 1992]. Figure 2 shows the typical shapes of windowed Fourier transform functions and wavelet.

The wavelet transform means that signal $s(t)$ is characterized by decomposition into a set of wavelet family with series of different frequency

bandwidth. For the decomposition of the signal $s(t)$ defined on real line, it is necessary to shift ψ along \mathbf{R} . Let \mathbf{Z} denote the set of integers;

$$\mathbf{Z} = \{ \dots -1, 0, 1, \dots \}.$$

The simplest way for ψ to cover all of \mathbf{R} is to consider all the integral shift of ψ ,

$$\psi(t - k), \quad k \in \mathbf{Z}. \quad (7)$$

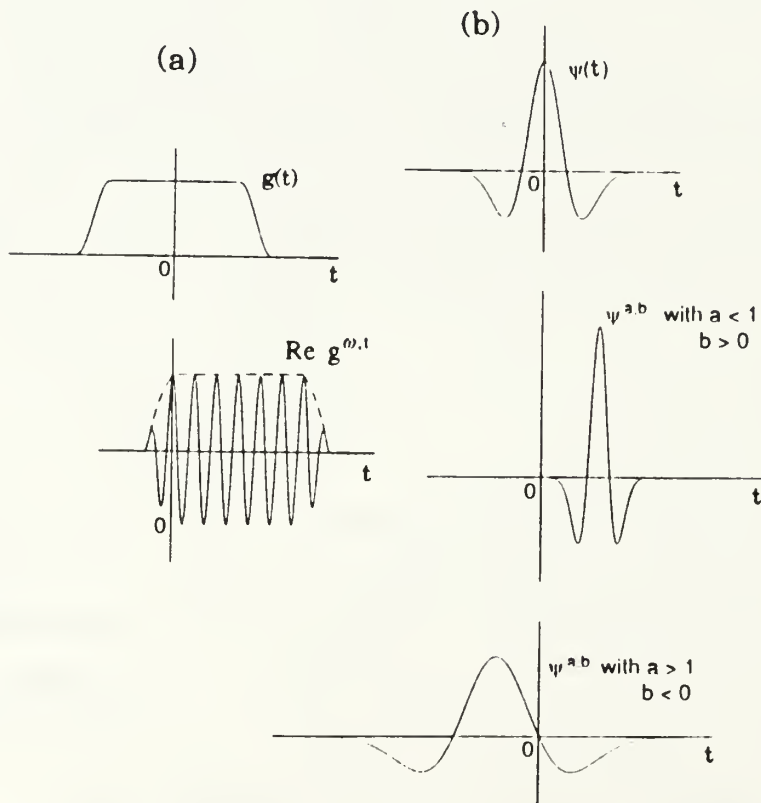


Figure 2. The typical shapes of (a) windowed Fourier transform function $g(t)$, (b) wavelet $\psi^{a,b}$, $\psi(t) = (1 - t^2) e^{-t^2/2}$ [Daubechies, 1992].

Next, as in Fourier transform, it must be also considered wavelets with different frequencies. It is considered wavelets with frequencies partitioned into consecutive 'octaves' (or frequency bands). For computational efficiency, it will be used integral power of 2 for frequency partitioning, that is, the small wavelets is considered as follows

$$\psi(2^j t - k), \quad j, k \in \mathbb{Z}. \quad (8)$$

From the equation (3), $\psi(2^j t - k)$ is obtained from the wavelet function $\psi(t)$ by dilation of $1/2^j$ and translation of $k/2^j$. An important particular case of the discrete wavelet transform which was found is that some wavelets $\psi(t)$ exist such that $\sqrt{2^j} \psi(2^j(t - 2^{-j}k))_{(j,k) \in \mathbb{Z}}$ is an orthonormal basis of $L^2(\mathbb{R})$ [Mallat, 1989].

As originally proposed by Morlet et al. (1982), ψ was a modulated Gaussian

$$\psi(t) = e^{i\omega_0 t} e^{-t^2/2} \quad (9)$$

and this function is selected to analysis the vibration of gear box for signal processing applications[Wang and McFadden, 1993]. The example of a shape for the modulated Gaussian wavelet is shown in figure 3. The Fourier transform of the first wavelet family $\psi(t/a)$, i.e., no translation, is

$$\hat{\psi}(a\omega) = a e^{-(\omega - \omega_0/a)^2 a^2/2} \quad (10)$$

which has analysis frequency ω_0/a . ω_0/a is a simple frequency parameter which determines the analyzing wavelet. We can easily see that equation (9) satisfies the admissibility condition equation (4). The analyzing bandwidth of the wavelet is proportional to $1/a$, thus having a constant relative bandwidth(BW), that is, $BW/(\omega_0/a) = \text{constant}$. This feature is also reflected in the narrow time window at higher frequency(i.e., at smaller a). In general, the function $\psi(t)$ is selected by its time and frequency localization properties [Daubechies, 1990].

The scale change may be performed by substituting $a = 2^{-j}$ for the computation efficiency. In this case the wavelet family is $\sqrt{2^j} \psi(2^j t)$, and the definition of the wavelet transform becomes

$$W(2^j, b) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{\infty} \psi\left(\frac{t-b}{2^j}\right) s(t) dt \quad (11)$$

In this report, the unique function $\psi(t)$ can be selected to be a well-behaved modulated Gaussian function, given by equation (9).

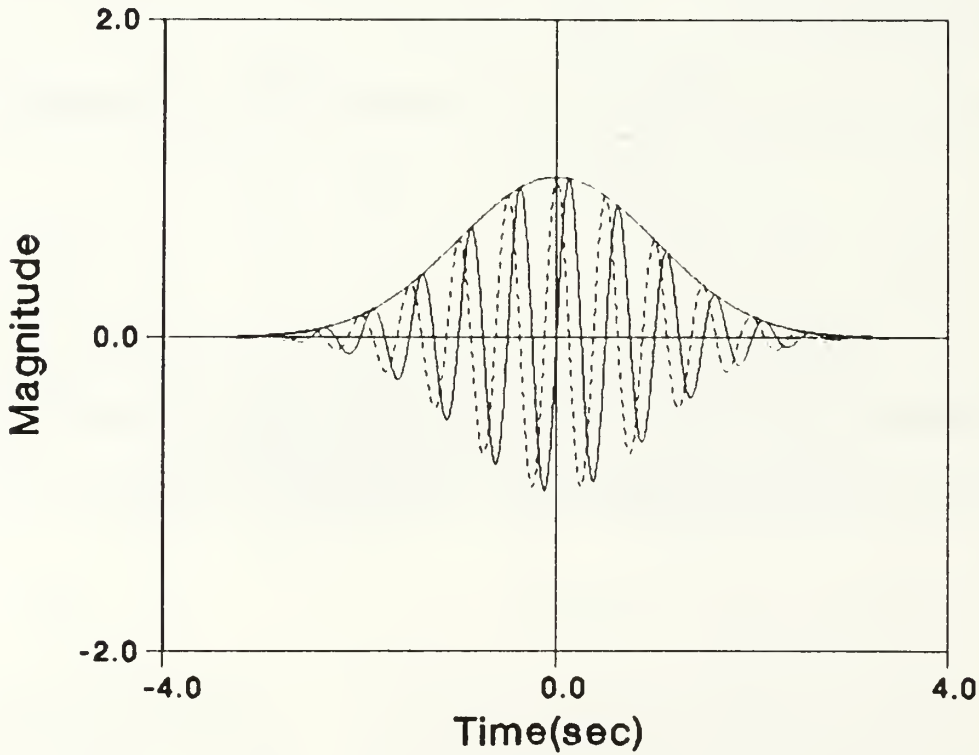


Figure 3. Example of modulated Gaussian wavelet.

$$(\psi(t) = e^{i\omega_0 t} e^{-t^2/2}, \omega_0 = 2\pi f_0, f_0 = 2 \text{ Hz})$$

III. TIME-FREQUENCY ANALYSIS

Suppose that ψ is any basic wavelet such that both ψ and its Fourier transform $\hat{\psi}$ are window functions which have centers and half widths of time and frequency domain given by t^* , ω^* , Δt , $\Delta \omega$, respectively. Then the wavelet transform of an analog signal $s(t)$ is given as follows.

$$W(a, b) = |a|^{-1/2} \int_{-\infty}^{\infty} s(t) \overline{\psi\left(\frac{t - b}{a}\right)} dt \quad (12)$$

Equation (12) localizes the signal with a time window

$$[b + at^* - a\Delta t, b + at^* + a\Delta t],$$

where the center of the window is at $b + at^*$ and the width is given by $2a\Delta t$. This is called time localization in signal analysis.

On the other hand, let set the Fourier transform of ψ

$$\eta(\omega) = \hat{\psi}(\omega + \omega^*), \quad (13)$$

where η is the Fourier transform of ψ , then η is also a window function with center at ω^* and width by $\Delta \omega$, and by Parseval identity, the wavelet transform in equation (12) becomes [Chui, 1992]

$$W(a, b) = \frac{a|a|^{-1/2}}{2\pi} \int_{-\infty}^{\infty} \hat{s}(\omega) e^{ib\omega} \overline{\eta\left(a\left(\omega - \frac{\omega^*}{a}\right)\right)} d\omega \quad (14)$$

where the phase shift of $e^{ib\omega}$ is determined by translation along time axis. Equation (14) is also localized information of spectrum $\hat{s}(\omega)$ of the signal $s(t)$ with frequency window

$$[\frac{\omega^*}{a} - \frac{1}{a}\Delta\omega, \frac{\omega^*}{a} + \frac{1}{a}\Delta\omega],$$

where the center of window is at ω^* / a and width is given by $2\Delta\omega / a$. This is called frequency localization.

From equation (12) and (14), time-frequency window of wavelet transform is as follows.

$$[b + at^* - a\Delta t, b + at^* + a\Delta t] \times [\frac{\omega^*}{a} - \frac{1}{a}\Delta\omega, \frac{\omega^*}{a} + \frac{1}{a}\Delta\omega] \quad (15)$$

The covered area by time-frequency window is the multiplication of time and frequency bandwidth around the center of window. The time-frequency window is shown figure 4. Eventually it is considered positive frequencies, i.e., $a > 0$, the basic wavelet ψ may be chosen that the center ω^* of $\hat{\psi}$ is a positive number. The ratio of the center frequency to the width of frequency band is given by

$$\frac{\omega^* / a}{2\Delta\omega / a} = \frac{\omega^*}{2\Delta\omega} \quad (16)$$

which is independent of the location of the center frequency. This is called constant percentage band width analysis or constant-Q frequency analysis. In this report, the octave band is used for the analysis of vibration signal. The frequency window along the frequency axis narrows for large center frequency ω^* / a and widens for small one and the time window is opposite to frequency window. The area of the window is a constant, given by $4\Delta t\Delta\omega$.

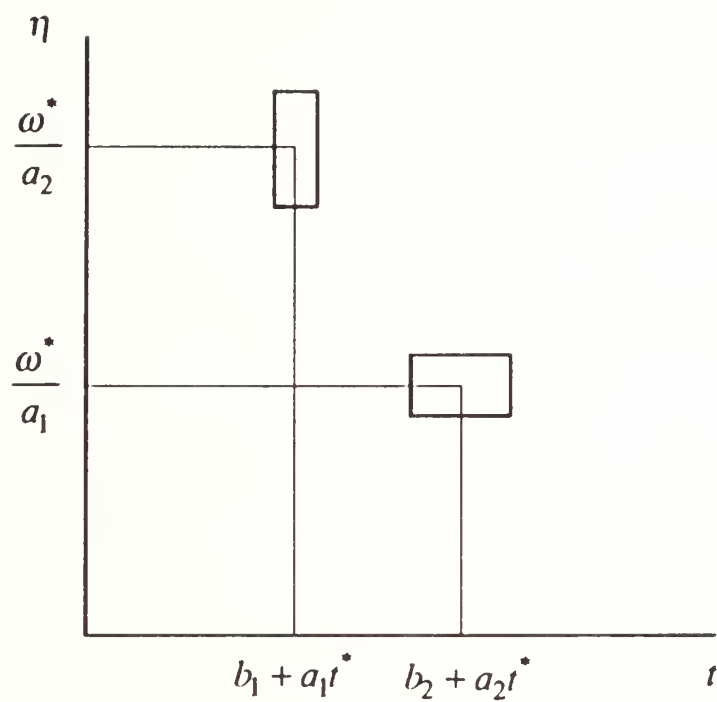


Figure 4. Time-frequency windows, $a_1 > a_2$.

IV. DISCRETE WAVELET TRANSFORM

In the continuous wavelet, the family is considered

$$\psi^{a,b}(t) = |a|^{-1/2} \psi\left(\frac{t-b}{a}\right) \quad (17)$$

where $b \in \mathbf{R}$, $a \in \mathbf{R}_+$ with $a \neq 0$, and ψ is admissible. \mathbf{R} denotes the real line and \mathbf{R}_+ denotes the positive real line. It is considered with discrete values for a and b . For the discretization of the dilation parameter, we select $a = a_0^m$, where $m \in \mathbf{Z}$, and the dilation step $a_0 \neq 1$ is fixed. For convenience, it assume $a_0 > 1$. If $a_0 = 1$, the wavelet transform may be similar to windowed Fourier transform. For $m = 0$, it seems natural as well to dicretize b by taking only the integer multiples of one fixed b_0 , where b_0 is appropriately chosen so that the $\psi(t - nb_0)$ cover the whole line. We arbitrarily fix $b_0 > 0$ in this report. For the different values of m , the width of $a_0^{-m/2} \psi(a_0^{-m} t)$ is a_0^m times the width of $\psi(t)$ defined at section III, so that the choice $b = nb_0 a_0^m$ will ensure that the discretized wavelets at level m cover the line in the same way that $\psi(t - nb_0)$ do. Thus it is selected, $a = a_0^m$, $b = nb_0 a_0^m$, where m, n range over \mathbf{Z} , and $a_0 > 1$, $b_0 > 0$ are fixed; the appropriate choices for a_0 and b_0 depend on the wavelet ψ and the characteristics of signal. The discrete form of equation (17) is given as following equation [Daubechies, 1992]

$$\begin{aligned} \psi_{m,n}(t) &= a_0^{-m/2} \psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right) \\ &= a_0^{-m/2} \psi(a_0^{-m} t - nb_0) \end{aligned} \quad (18)$$

For the computation efficiency, we assume that $a = 2^m$, that is, $a_0 = 2$, where m is termed the octave of the transform. This means that the

frequency resolution of wavelet has a octave band. The integral equation (3) yields a wavelet series as following equation by using equation (18).

$$W(2^m, nb_0) = \frac{1}{\sqrt{2^m}} \int_{-\infty}^{\infty} \overline{\psi\left(\frac{t - nb_0}{2^m}\right)} s(t) dt \quad (19)$$

At the discrete wavelet transform, the finite energy for the wavelet transform is not equivalent to finite energy for the wavelet series. It depends on the sampling grid as well as the function $\psi(t)$. In addition, it often take b to be a multiple of a .

$$W(2^m, n2^m) = \frac{1}{\sqrt{2^m}} \int_{-\infty}^{\infty} \overline{\psi\left(\frac{t}{2^m} - n\right)} s(t) dt \quad (20)$$

A logical step in applying the theory to discrete signal is to discretize the integral in equation (20) as follows.

$$W(2^m, n2^m) = \frac{1}{\sqrt{2^m}} \sum_k \overline{\psi\left(\frac{k}{2^m} - n\right)} s(k) \quad (21)$$

Octave m is only output every 2^m samples. In this form the resulting algorithm will not be translation invariant [Mallat, 1982]. The discrete wavelet transform is highly not invariant under translations. In practice one does not use an infinite number of scales, but cuts off very low and very high frequencies.

V. EXAMPLES AND DISCUSSIONS

A signature generated by machinery involves many informations about its operating condition. It can be obtained the information about the operating condition of machinery by applying the analysis tools for the vibration records. Wavelet transform is a new tool that is particularly suited for time-frequency analysis of nonstationary or stationary signals. There are many advantages of using wavelet transform for both steady and transient signals. We will discuss the performance of the wavelet transform by using simple example and compare with pseudo Wigner-Ville distribution(PWVD) in time-frequency domain analysis.

Before showing some examples, it is necessary to discuss how best to describe the results. We have found that 3-D map and 2-D map of wavelet transform are a useful presentation for many applications. The square of the amplitude in equation (21) has the unit power/Hz. The distribution of the amplitude square over the individual wavelet and position can now be seen as figure 5. If the length of sampled data is shorter than the wavelet size, the distribution at lower wavelet level, i.e., low frequency, has the value at only one position.

In order to describe the results of wavelet transform, we use the 3-D and 2-D(for the complicated signal) graphics. And for graphic, the results of that is distributed and reduced to 256(3-D) or 512(2-D) data point along the time axis. Frequency axis is a log scale (octave scale or wavelet level) and time axis is a linear scale in figures of wavelet transform.

A. Harmonic wave with stepwise frequency changes

Figure 6 shows (a) the pure sine wave with stepwise frequency changes 500 Hz, 250 Hz and 100 Hz, (b) its PWVD and (c) the wavelet transform. The wavelet transform and PWVD well represent the time delay and the

frequency components of signal. The wavelet transform is a result with frequency partitioned into consecutive octaves for computational efficiency. Then the magnitude of 100 Hz is dispersed. But the wavelet transform clearly describes the time delay. From these figures, we can see that the PWVD has the higher resolution than the wavelet transform in frequency line. However the computation time of PWVD is extremely higher than the wavelet transform. Figure 7 shows the wavelet transform of the sine wave with 500 Hz in time from 0.085 sec to 0.17 sec. the wavelet transform well represents the time delay and the frequency band of the signal.

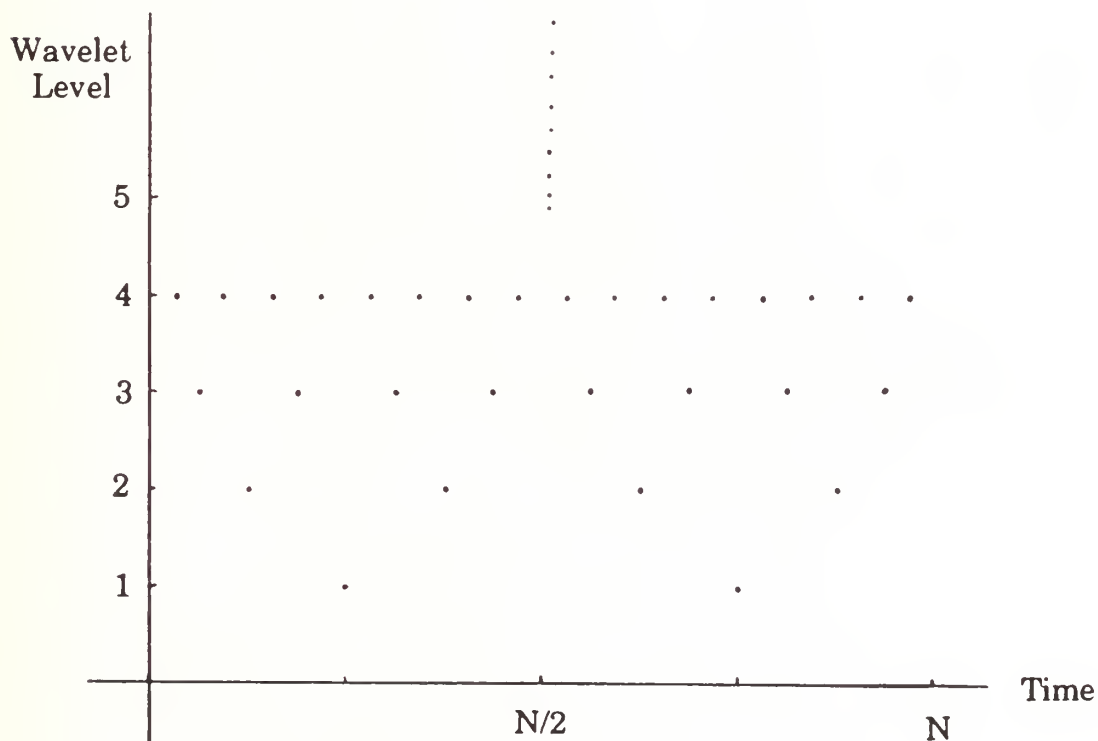
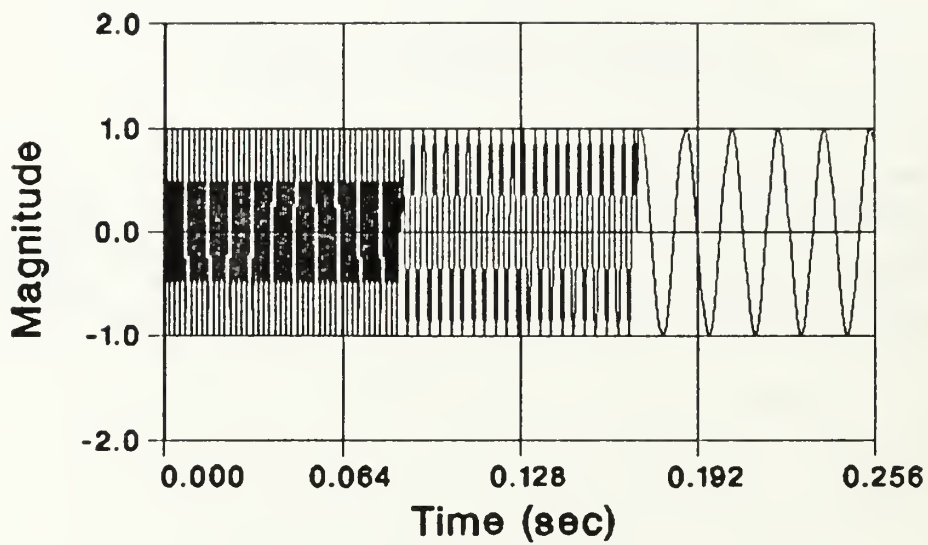
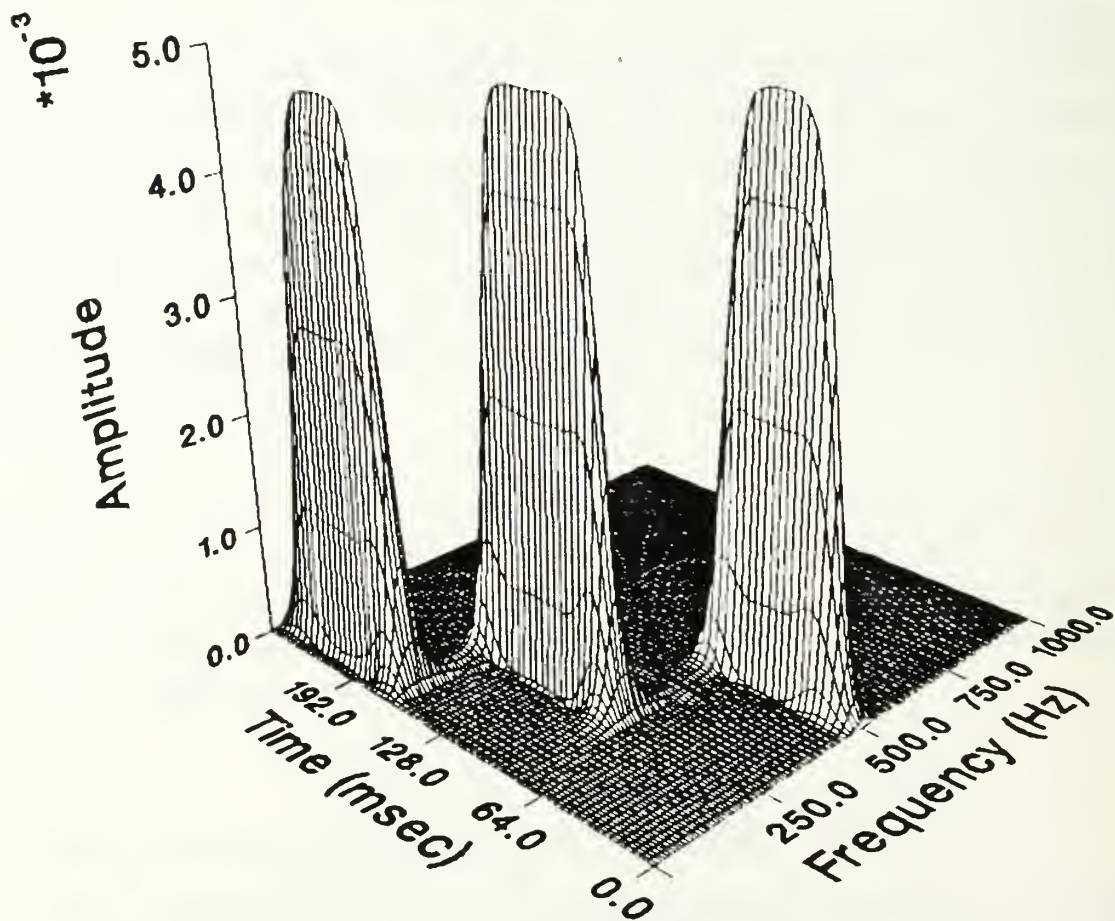


Figure 5. The lattice of time-frequency localization of wavelet transform
(N = Number of data points)

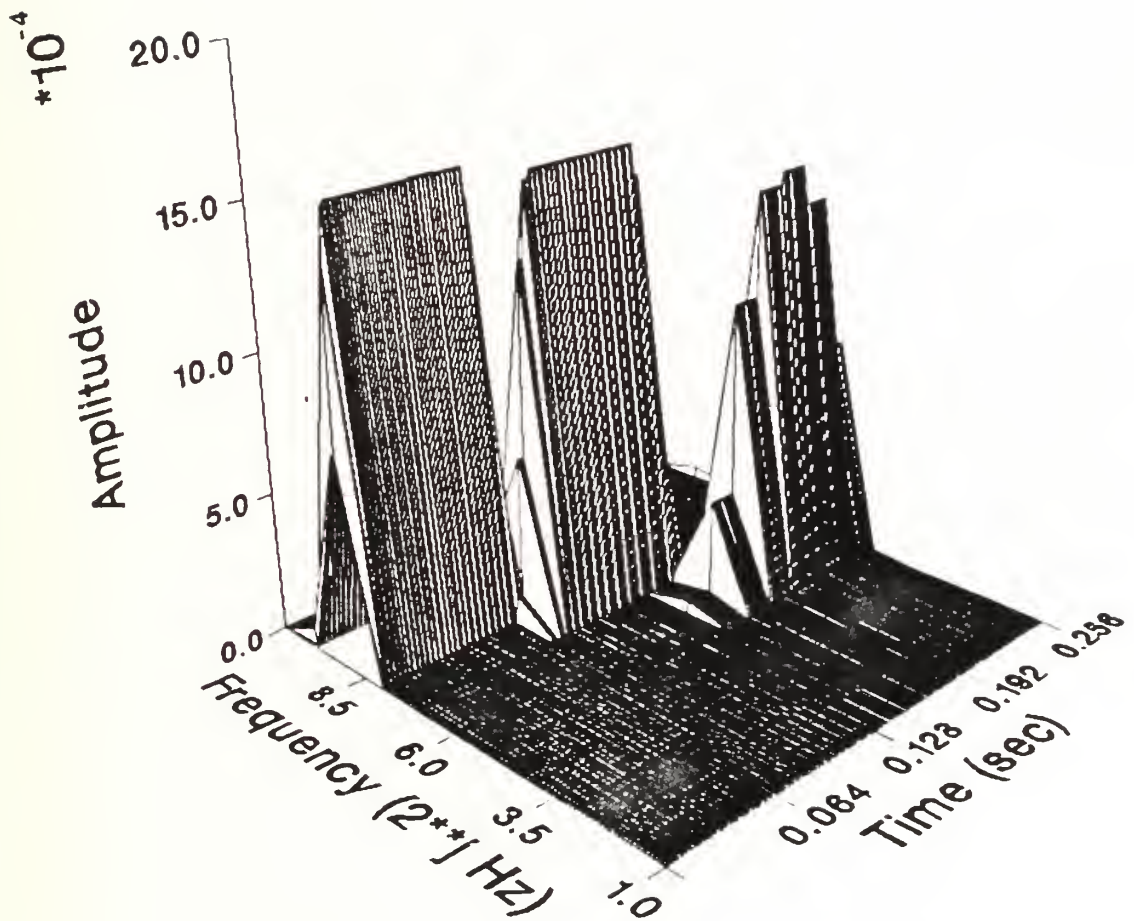


(a)



(b)

Fig.6 (continued)



(c)

Figure 6. Time-frequency localization of PWVD and wavelet transform: (a) signal $s(t)$, (b) its PWVD and (c) its wavelet transform ($f_s=2000$ Hz, $N=512$).

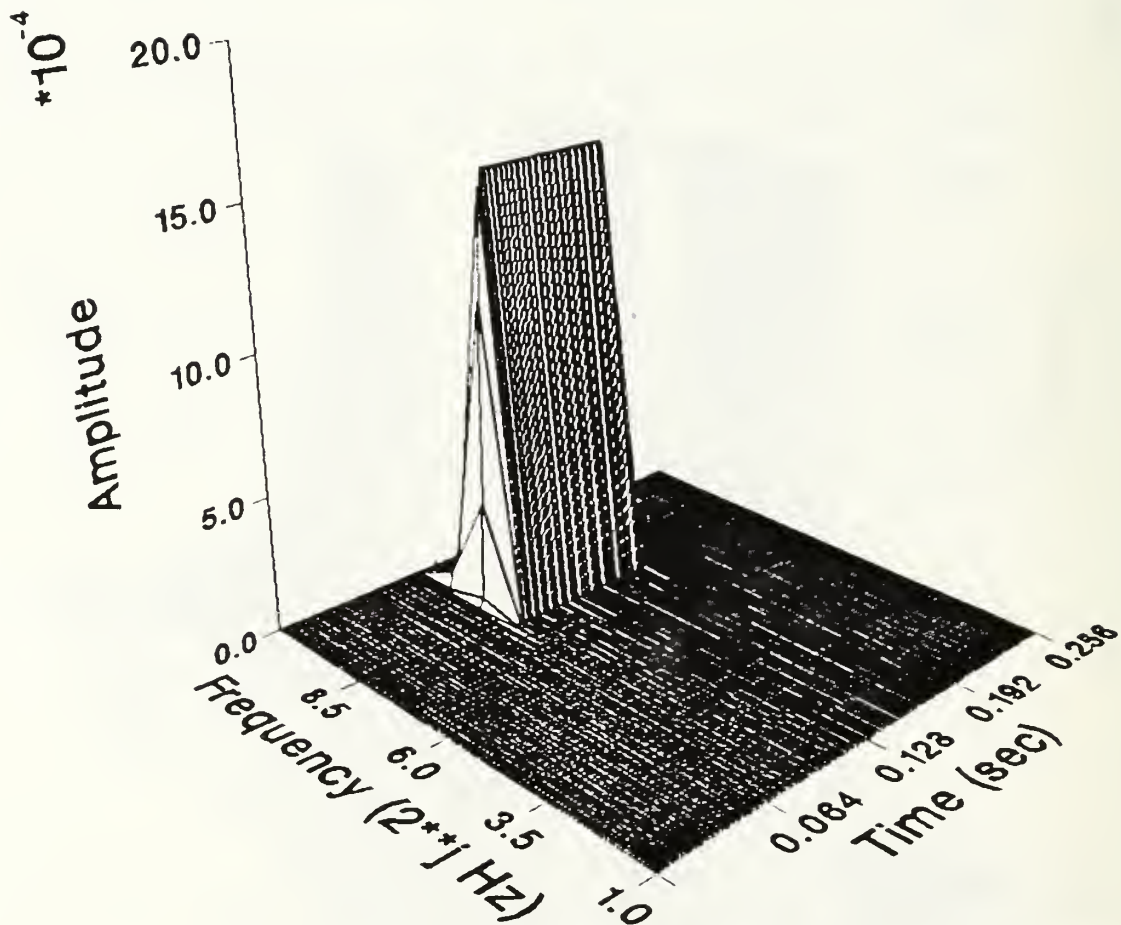
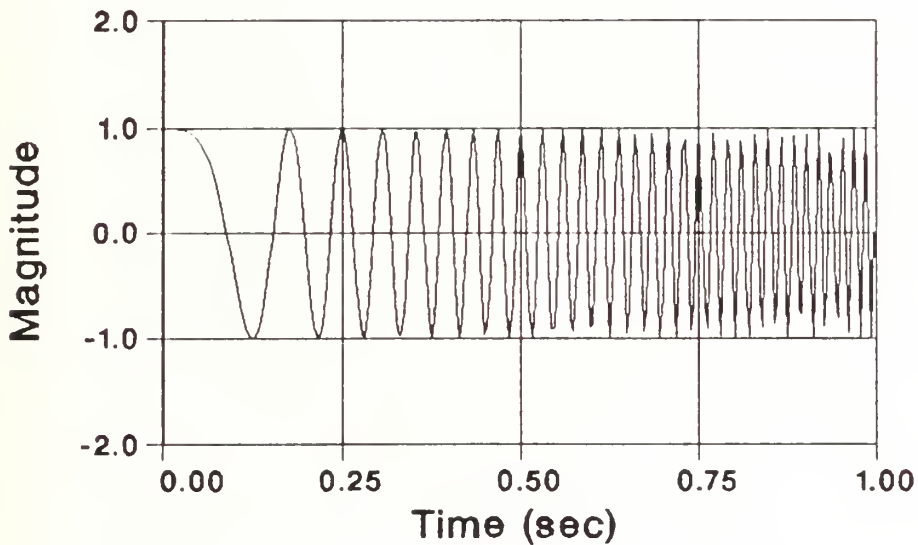


Figure 7. Wavelet transform for step sine wave ($f = 500$ Hz); $f_s = 2000$ Hz, $N=512$.

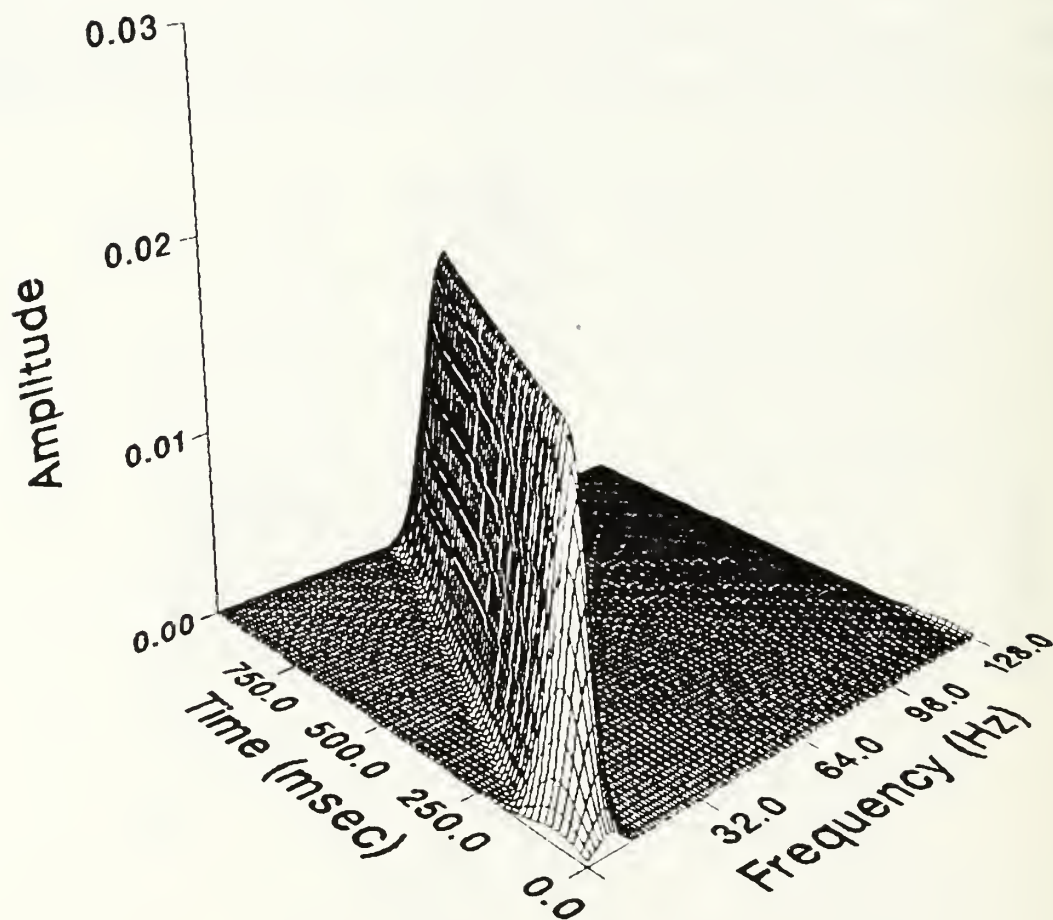
B. Swept harmonic wave

The effect of sweep rate on PWVD was well investigated at Jeon and Shin (1993), and Shin, Jeon and Spooner (1993). Figure 8. shows (a) the swept cosine wave with the sweep rate 32 Hz/sec, (b) its PWVD and (c) its wavelet transform. From this figures, we can see that PWVD is a useful tool for analysis of the signal with fast frequency change in time. However if the records of signal is longer, the computation time may be much needed. The result of the wavelet transform does not clearly represents the sweep condition but well describes the change of frequency range with time.



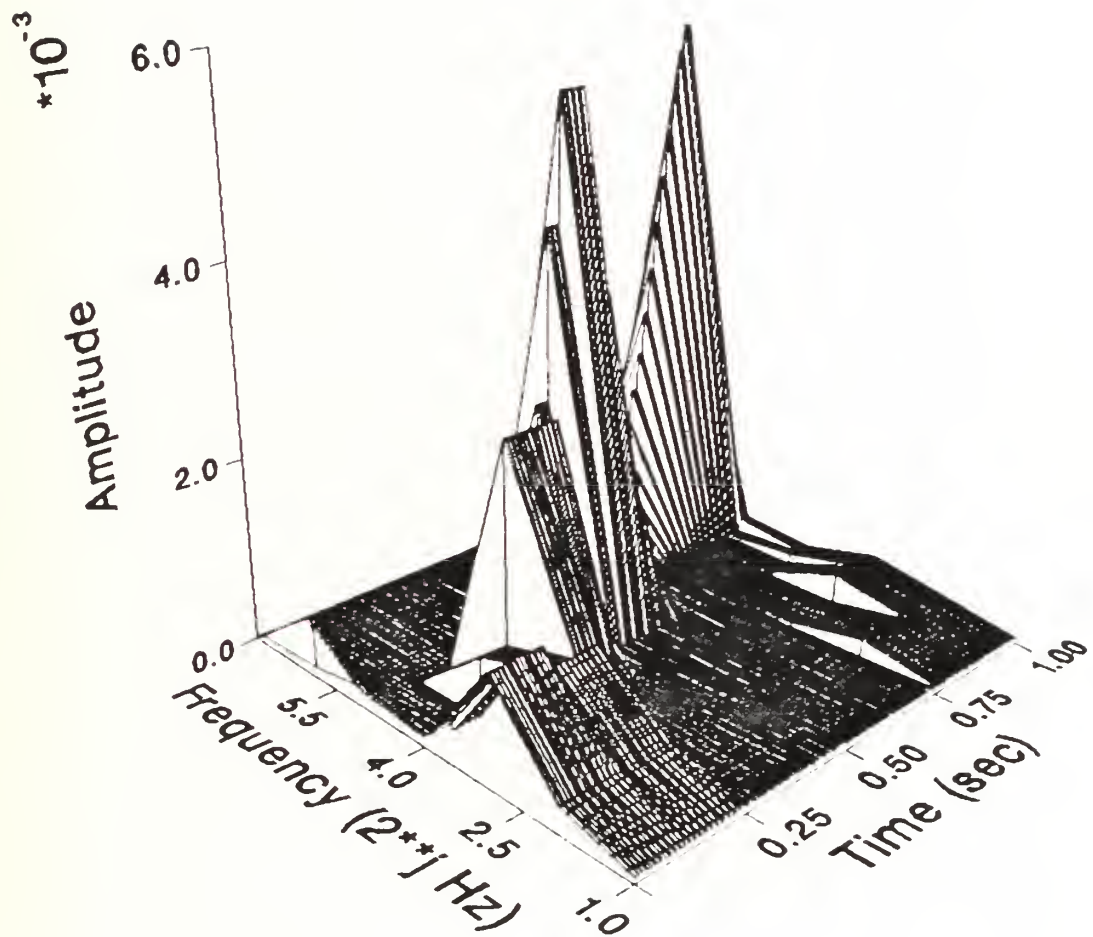
(a)

Fig.8 (continued)



(b)

Fig.8 (continued)



(c)

Figure 8. Time-frequency localization of the PWVD and wavelet transform: (a) signal $s(t) = \cos(2\pi 32 t^2)$, (b) its PWVD and (c) its wavelet transform ($f_s = 256$ Hz, $N = 256$).

C. Harmonic wave with glitches

The interesting phenomena on the signal with an abnormal component as a fault were investigated. Figure 9 shows (a) the harmonic wave with glitch at a small region, (b) is PWVD and (c) its wavelet transform. It can be seen that both PWVD and wavelet transform of the signal figure 9(a) well represents the location of each glitch and its frequency components. Figure 10 is the result of wavelet transform in case of sampling frequency 8192 Hz. From these figures, it can be clearly seen that the wavelet transform is very useful tool in the analysis of the signal required higher time resolution. Figure 9(c) shows the glitch components more clearly than PWVD because the wavelet transform has the very narrow time window in high frequency region. This characteristic of the wavelet transform is useful to detect the fault or glitch although the fault is small and to monitor the condition on any vibrational machinery under the steady operation condition. Also the wavelet transform is more effective for the analysis of signal which the time record length is long, since the sweep along the frequency line is octave step.

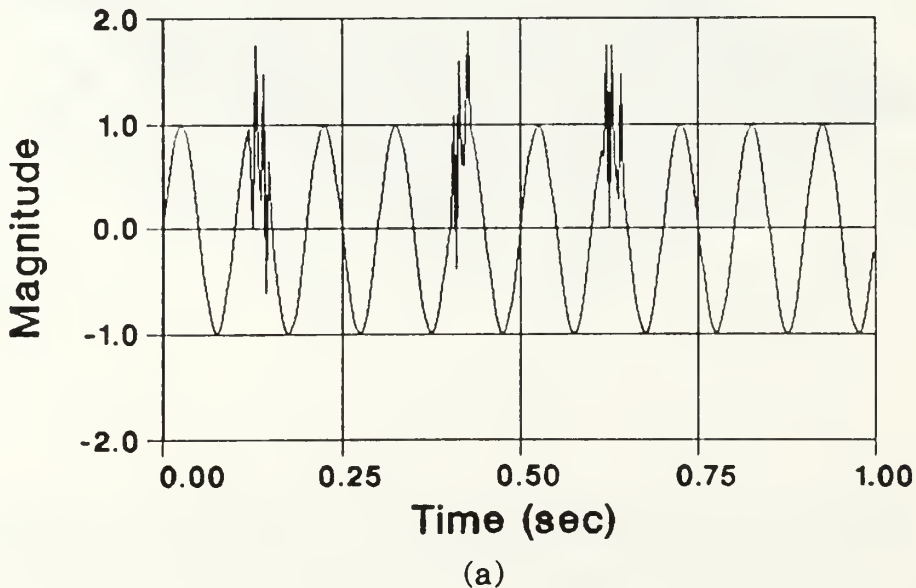
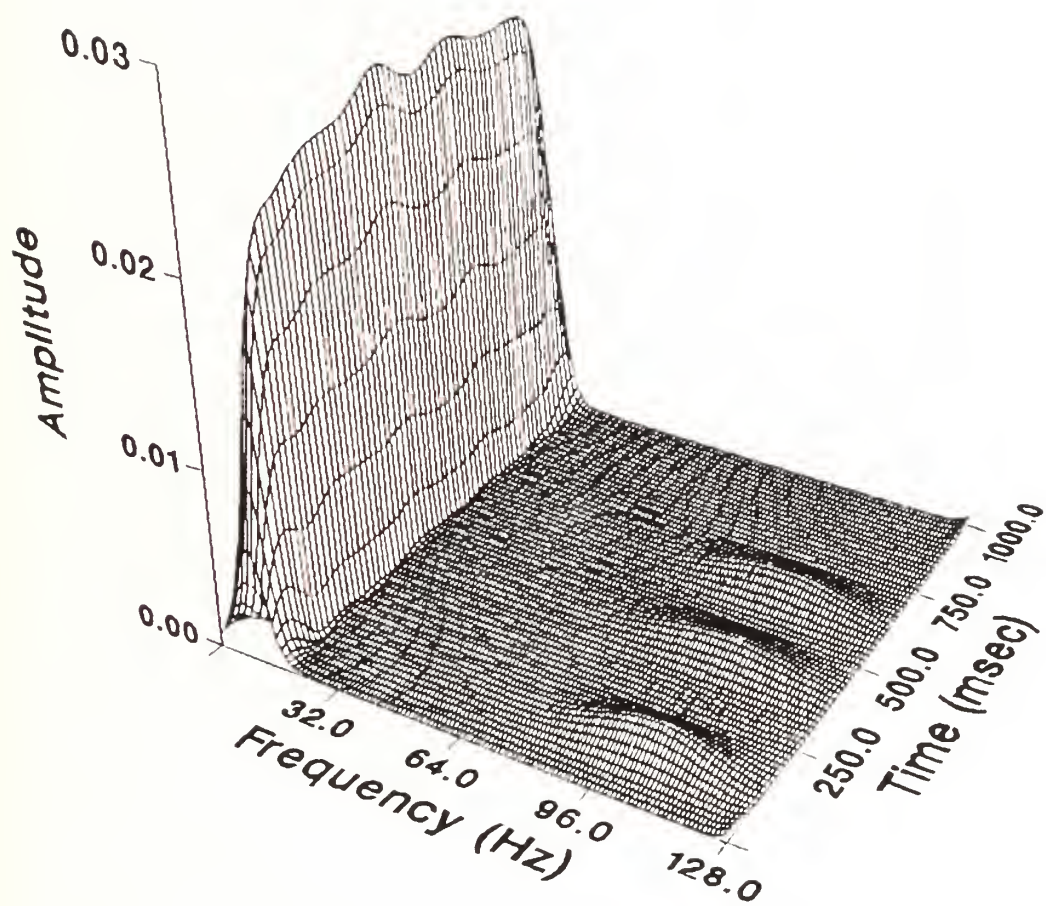
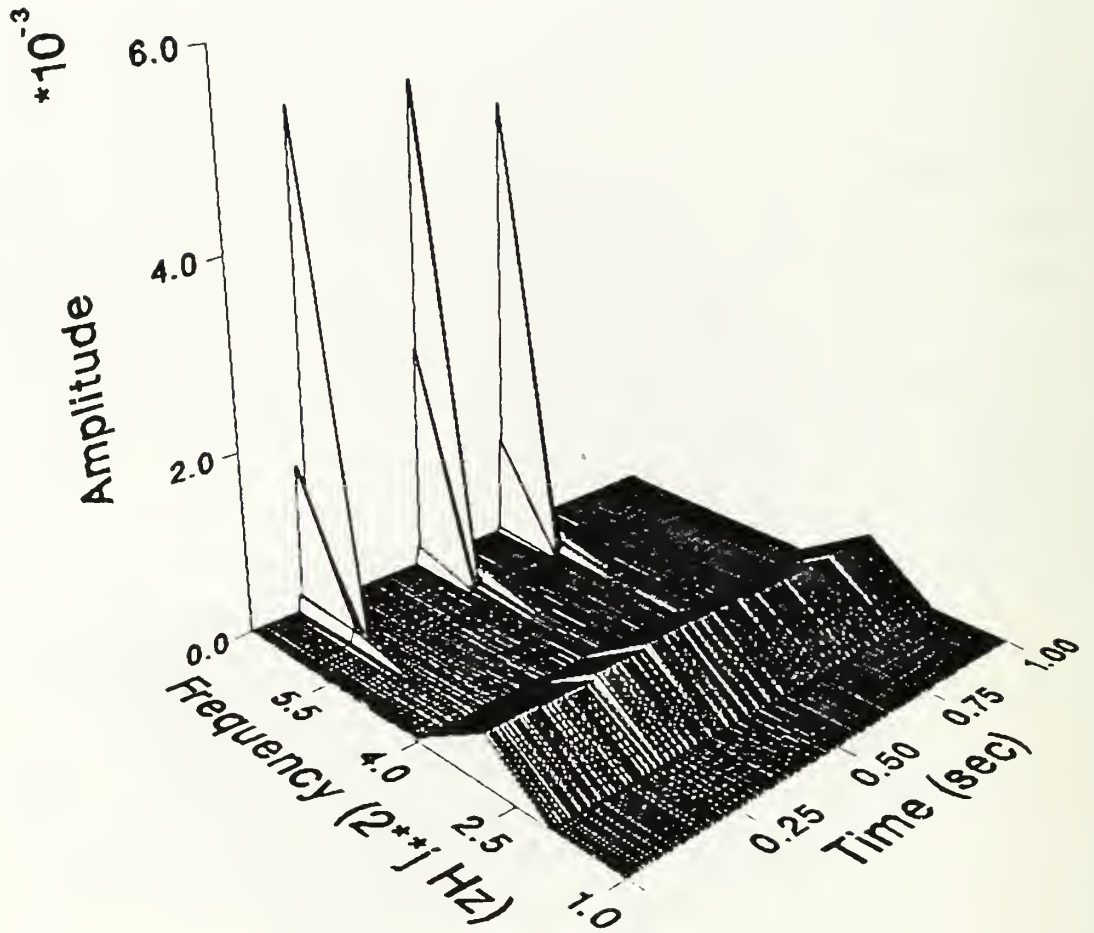


Fig.9 (continued)



(b)

Fig.9 (continued)



(c)

Figure 9. Time-frequency localization of PWVD and wavelet transform: (a) the signal $s(t)$ [Jeon and Shin, 1993], (b) its PWVD and (c) its wavelet transform ($f_s = 256$ Hz, $N = 256$).

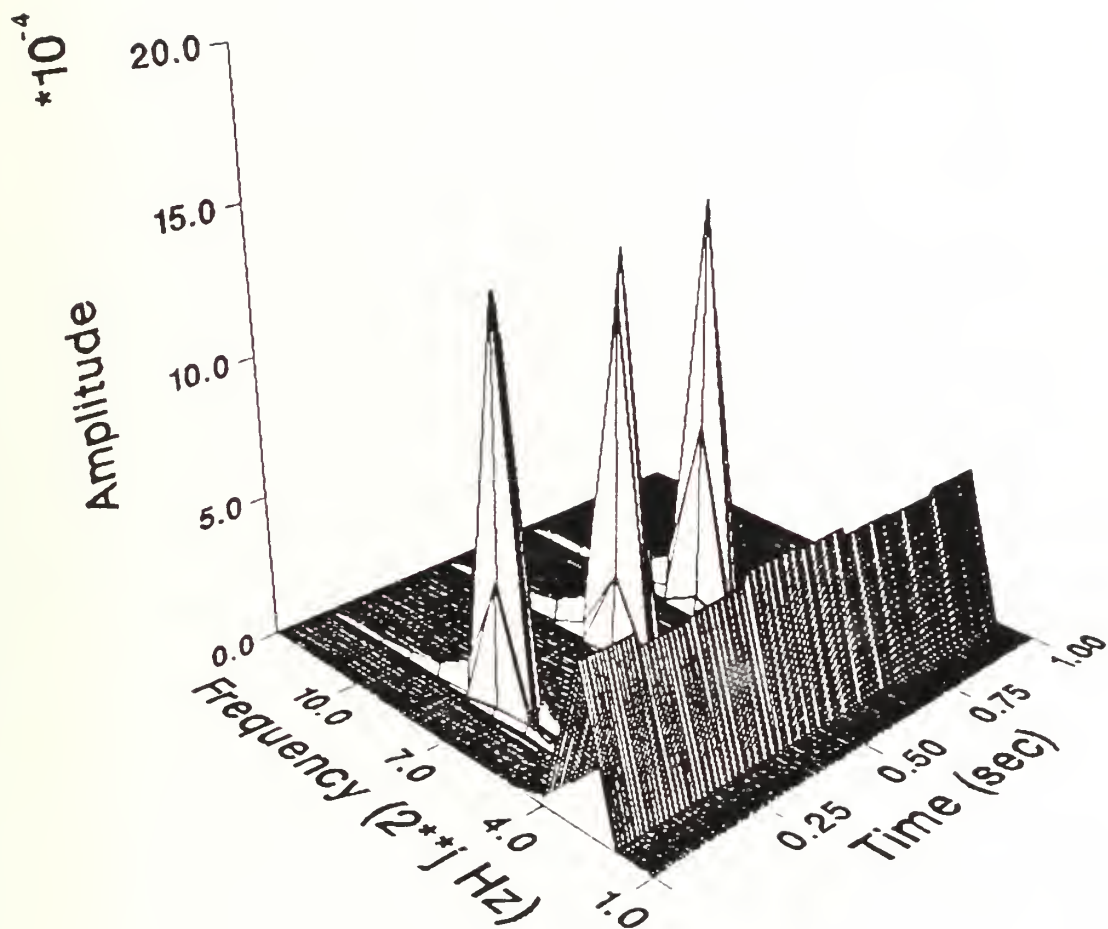


Figure 10. Time-frequency localization of wavelet transform for the signal Fig. 9(a) ($f_s = 8192$ Hz, $N = 8192$).

D. Harmonic wave with pulse

Figure 11 illustrates about the signal including small changes generated by early damage. In practice, this signal is not given by this continuous expression, but by samples, and adding a δ -function is then approximated by adding a constant to one sample only. The example signal is generated by following equation.

$$s(t) = \sin(2\pi 100 t) + \sin(2\pi 500 t) + 1.5 \delta(t-0.049) + 1.5 \delta(t-0.061) \quad (22)$$

From this figure, we can see that the wavelet transform has the great advantage for the analysis of the signature including the small disturbance. PWVD does not give the exact information about time delay of pulse but well represents about the frequency components of main signatures. The wavelet transform does not describe the magnitude of the main frequency components but well represents the time delay of pulse and is obtained the result by very short computation time. From this example, the wavelet transform is very useful tool to detect the fault although that is very small region on time axis.

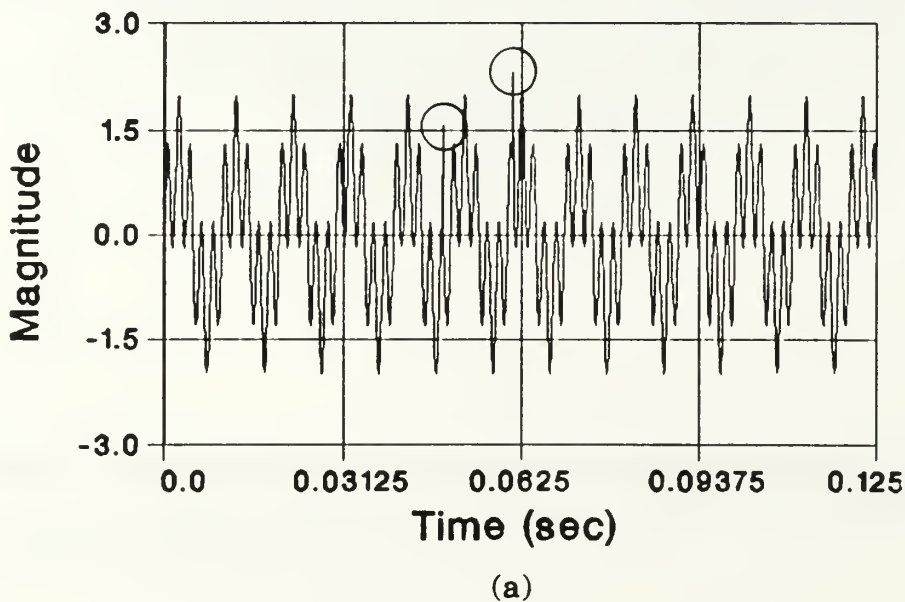
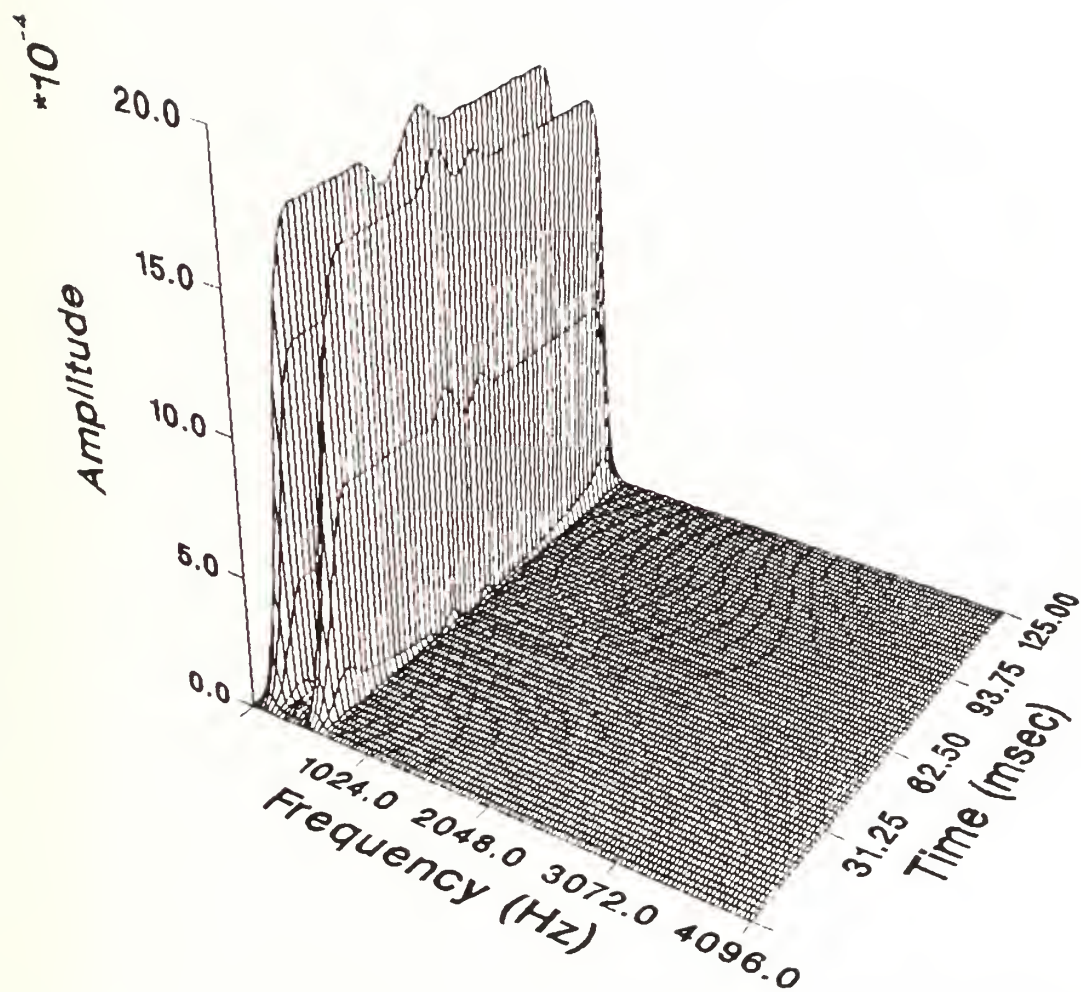
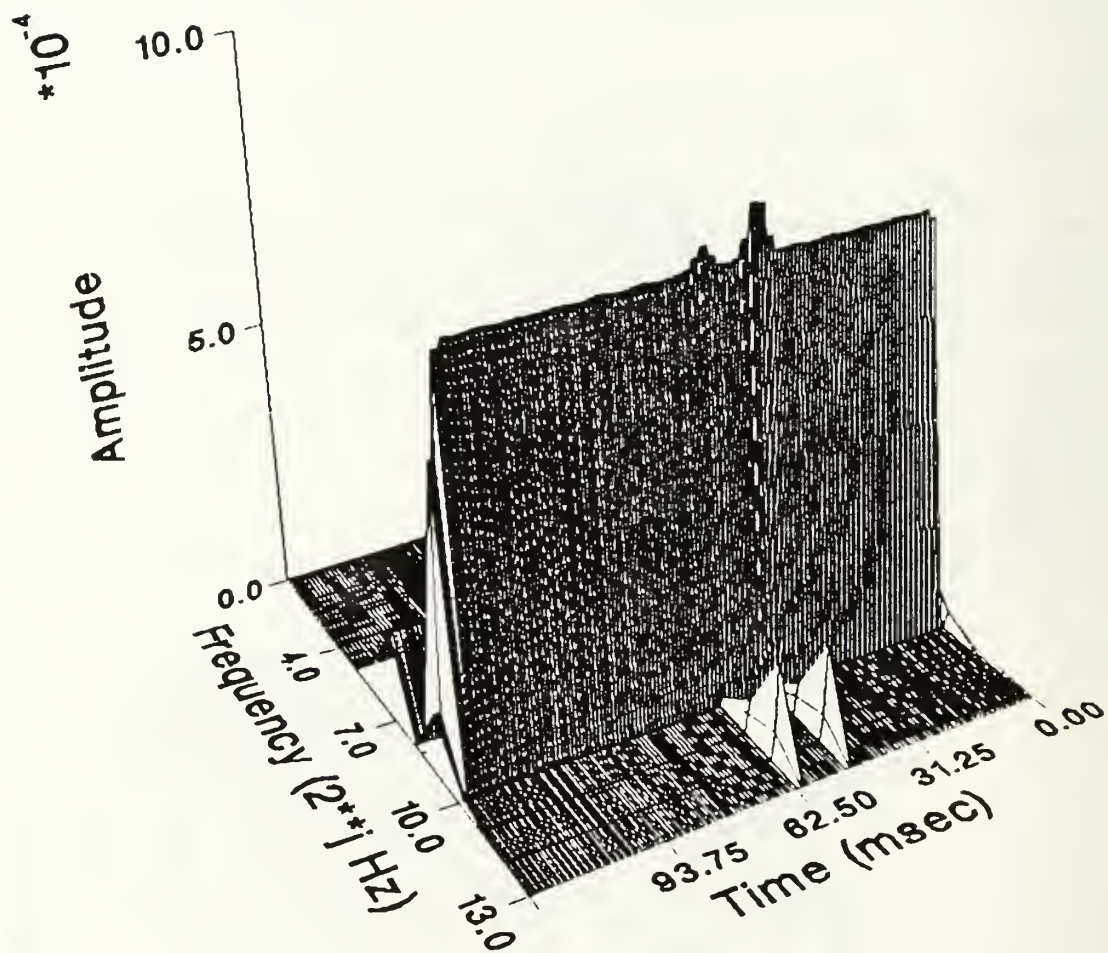


Fig.11 (continued)



(b)

Fig.11 (continued)



(c)

Figure 11. Time-frequency localization of PWVD and wavelet transform: (a) the signal $s(t)$, (b) its PWVD and (c) its wavelet transform ($f_s = 8192$ Hz, $N = 1024$)

E. Actual pump signal

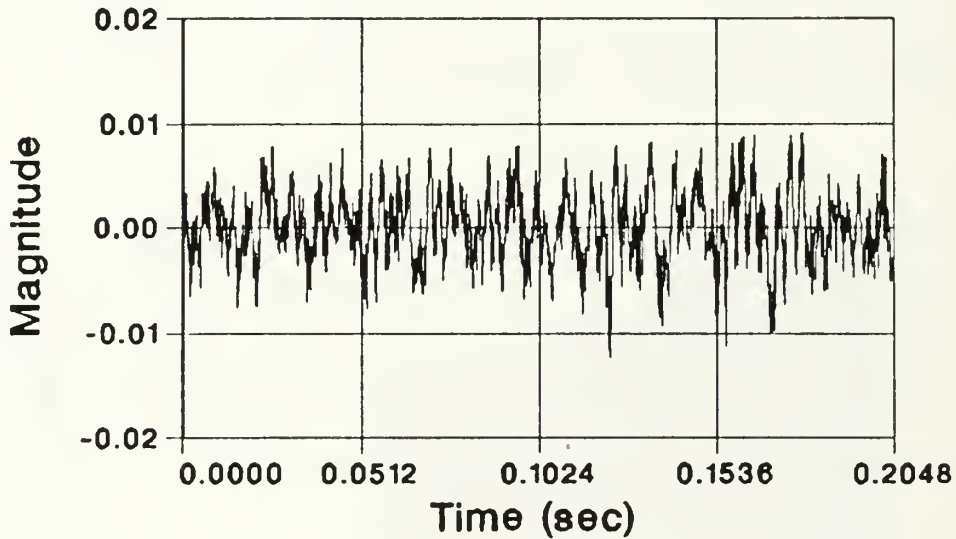
The signal of actual pump was measured at the steady state speed without and with abnormal condition. Figure 12 show the time signal pattern for each condition, and figures 13 and 14 show the results of wavelet transform by using 3-D or 2-D graphics. Also figure 15 are the results of pseudo Wigner-Ville distribution. These figures show a very interesting results.

From these figures, we can easily find the abnormal condition. At 13th frequency band of figure 13(a) and (b), the results of wavelet transform obviously show the different condition and pattern for each case. And also at 8th frequency band, the small changes of patterns can be seen. Figure 14(a) and (b) well represent the operation condition although the shape is more complicate and we can see the abnormal state of pump.

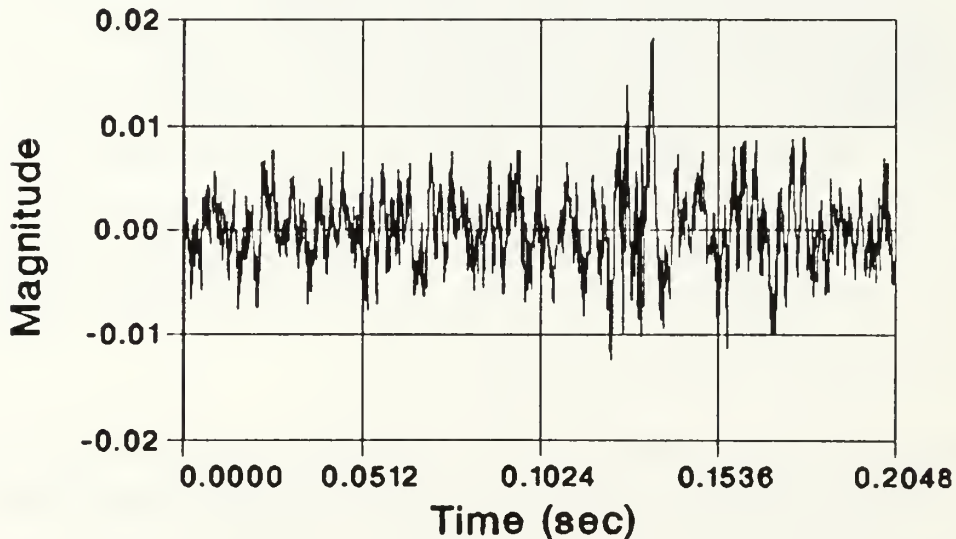
In this case, if one wavelet to have 13th frequency band is used, it gives good results for diagnosis and vibration condition monitoring as very short computation time. Figure 15 are PWVD. Also PWVD well represents the abnormal condition but the computation time is very long than that of wavelet transform. In the case of wavelet transform, it is possible to independently compute for each wavelet level different from PWVD. The difference of computation time for the wavelet transform and PWVD is about 100 times for the number of sample data $N=2048$ in the calculation of a whole plane. At VAX3520, the computation time is 18 seconds for wavelet transform and about 30 minutes for PWVD.

Especially the wavelet transform may be very useful to detect the small disturbance over long record length and to analyze the signals which has a long time duration and intermittent abnormal condition such as non-rotating machinery. The advantage of the Wigner-Ville distribution is that, unlike the wavelet transform or the windowed Fourier transform, it does not introduce a reference function(such as wavelet or window function in Eq.(3) and (1)) against which the signal has to be integrated and the short

time signal. The disadvantage is that the signal enters in Wigner-Ville distribution in a quadratic rather than linear way, which causes many interference phenomena as shown in references Jeon and Shin (1993), and Shin, Jeon and Spooner (1993). Wigner-Ville distribution may be useful in some application for signals which have a very short time duration.

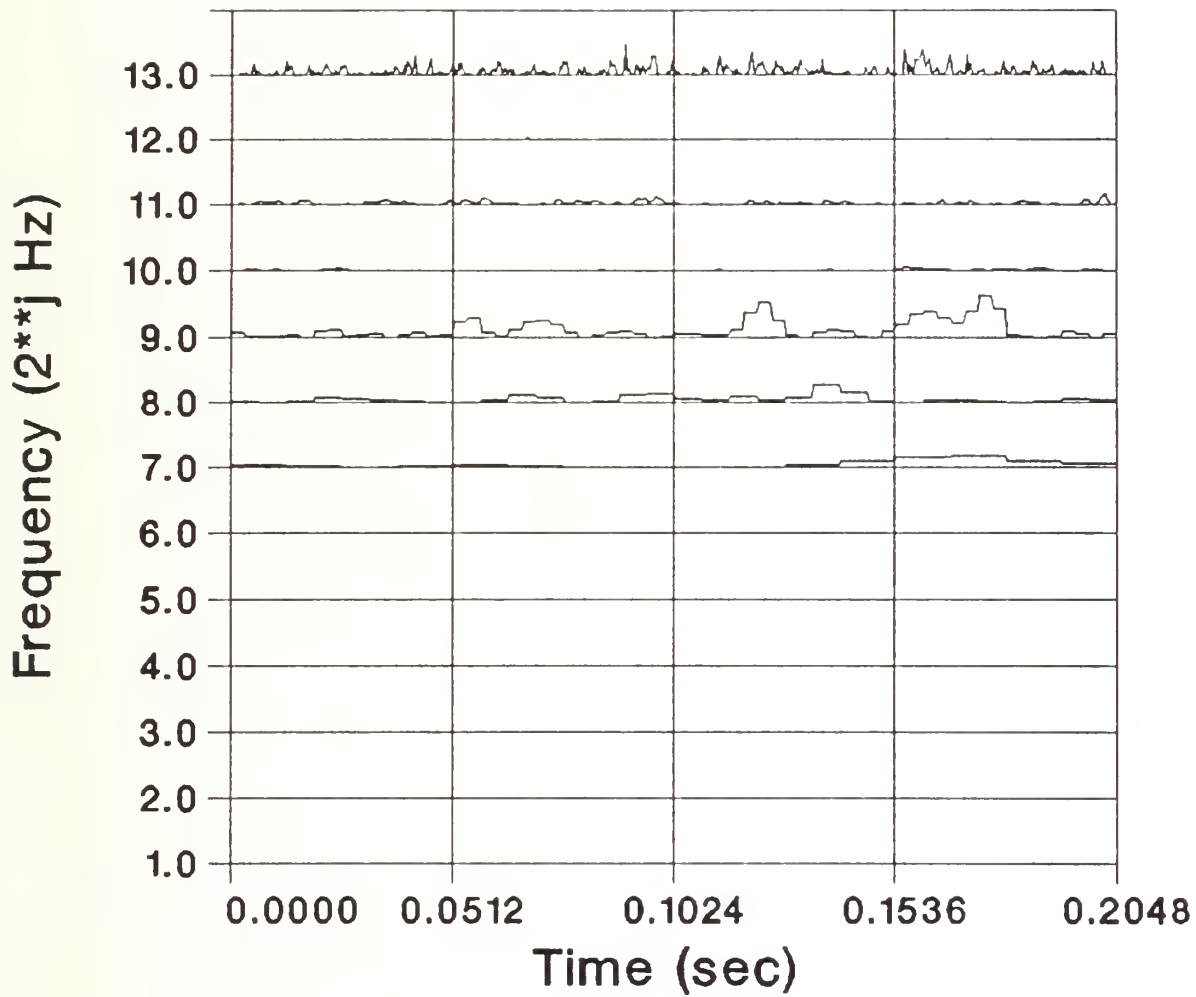


(a)



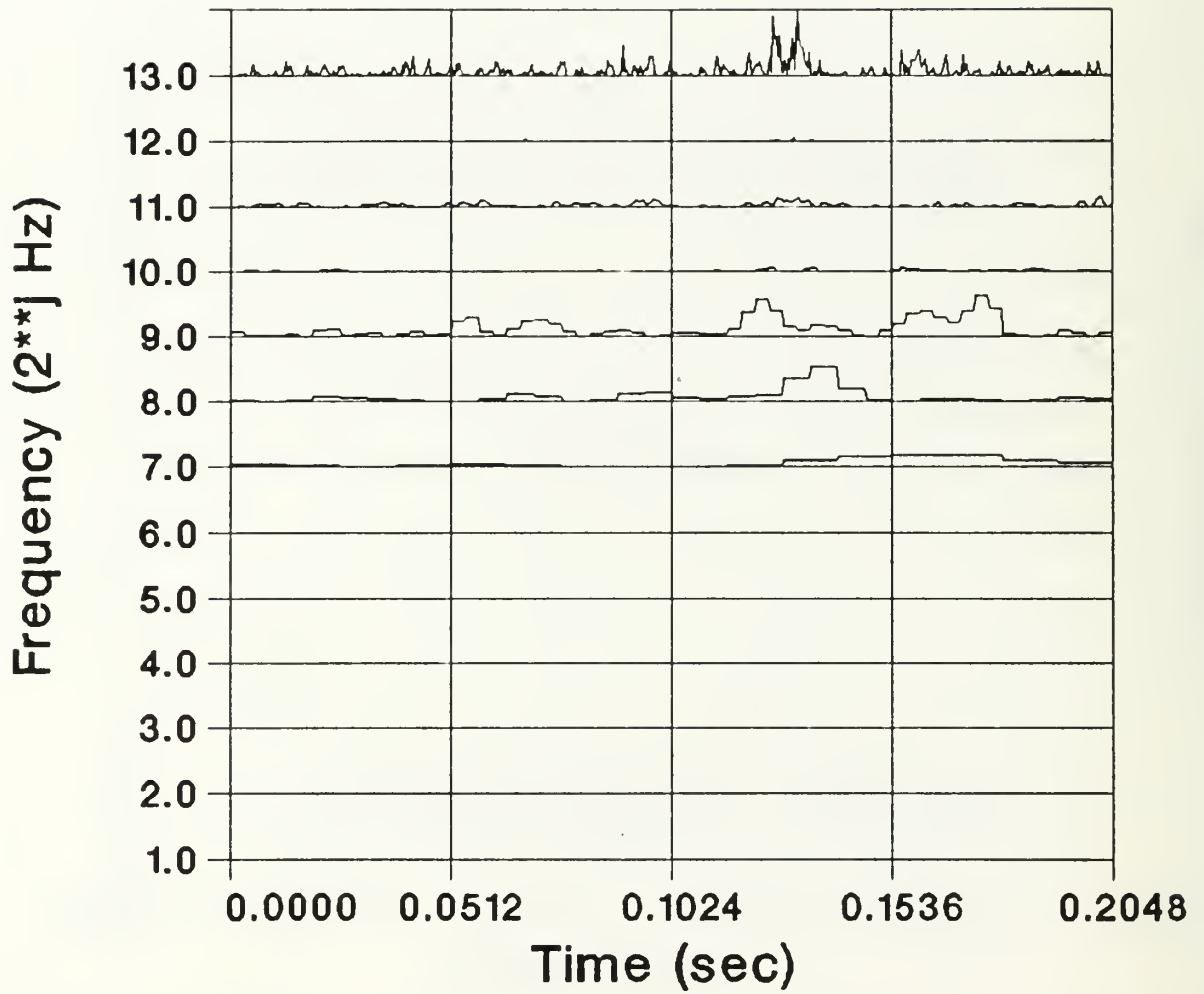
(b)

Figure 12. Time patterns of actual pump signal (a) without and (b) with abnormal condition.



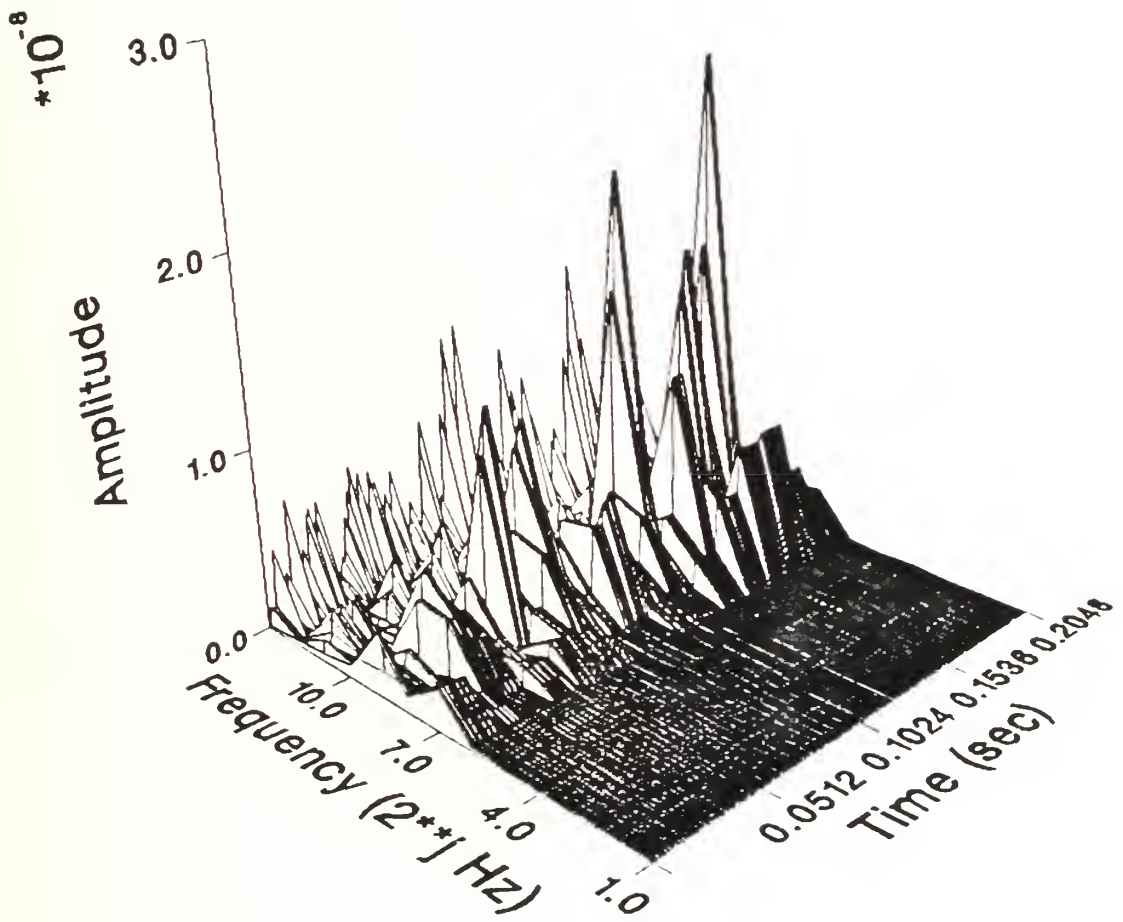
(a)

Fig.13 (continued)



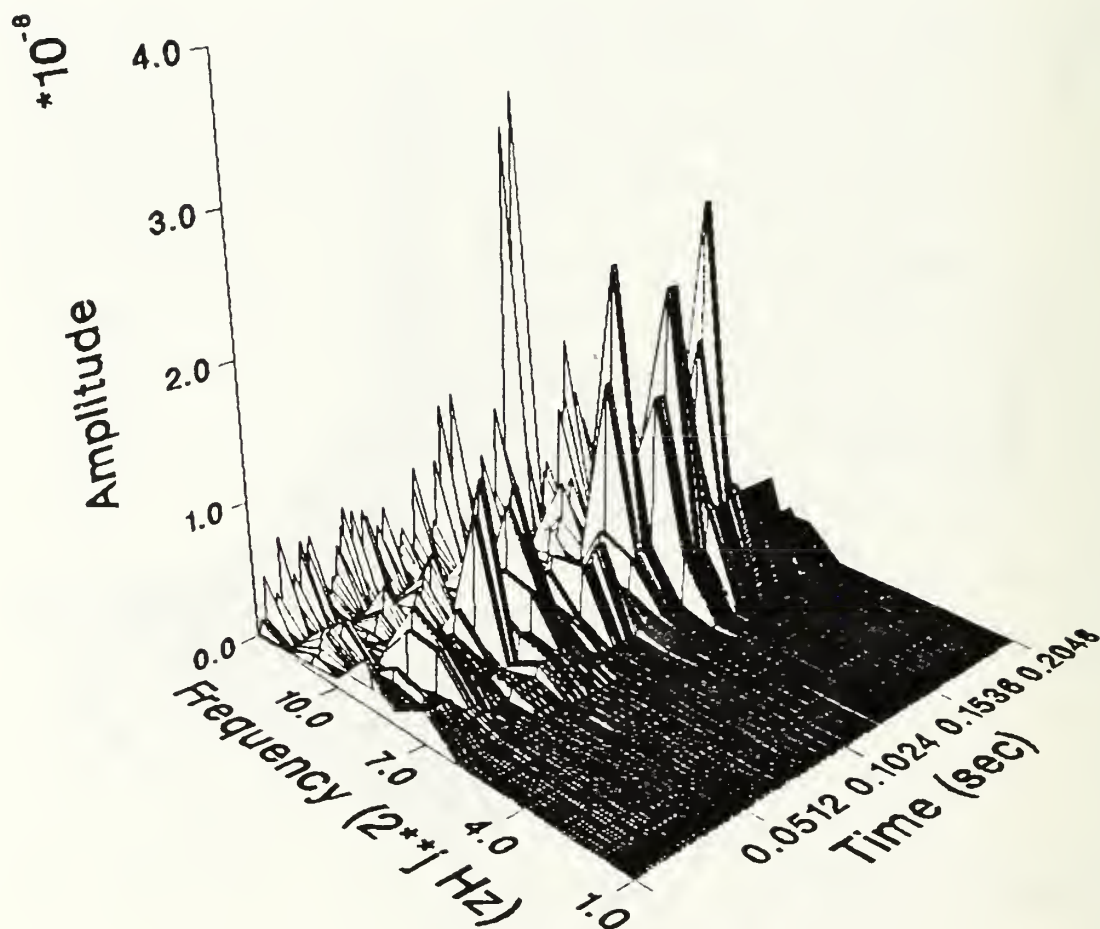
(b)

Figure 13. Time-frequency localization 2-D map of wavelet transform for Fig. 12(a) and (b), respectively ($f_s = 10$ kHz, $N=2048$).



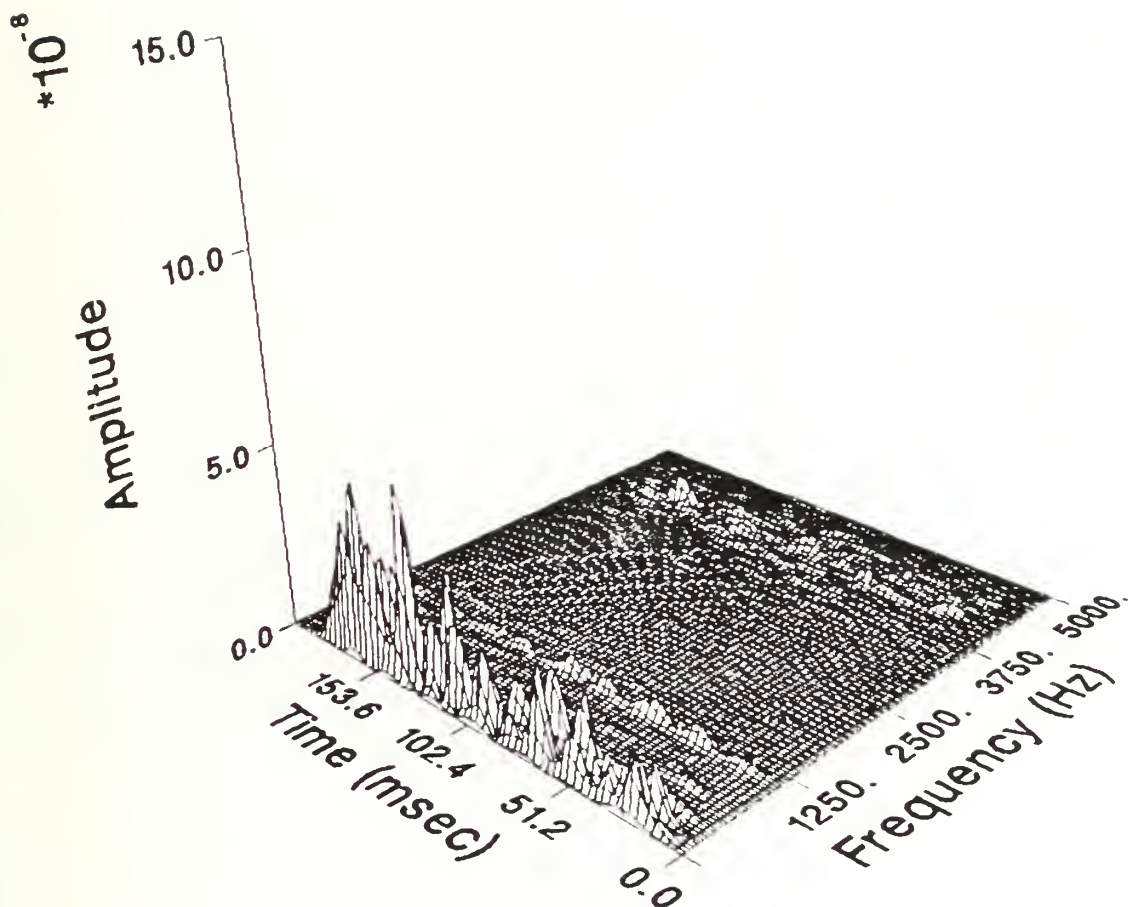
(a)

Fig.14 (continued)



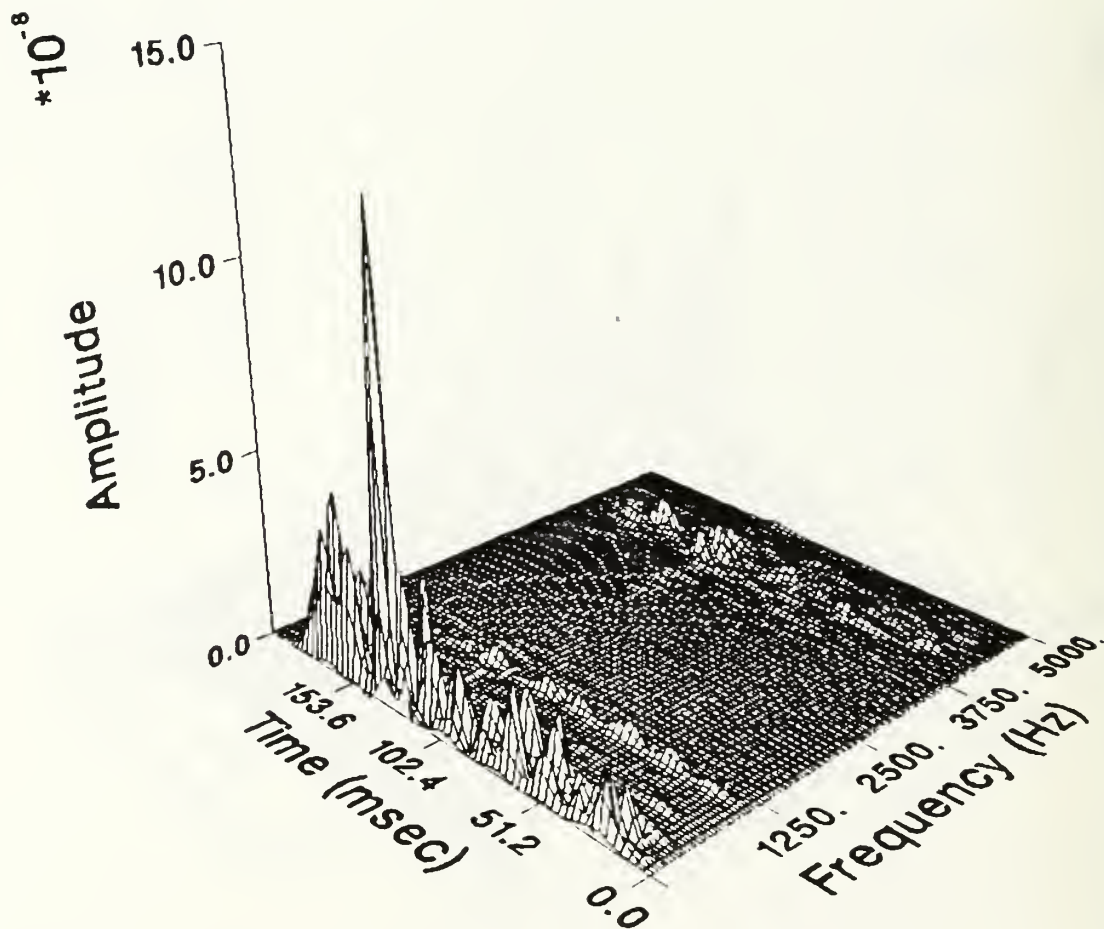
(b)

Figure 14. Time-frequency localization 3-D map of wavelet transform for Fig. 12(a) and (b), respectively ($f_s=10$ kHz, $N=2048$).



(a)

Fig.15 (continued)



(b)

Fig.13 Time-frequency localization of PWVD for Fig. 12(a) and (b), respectively ($f_s = 10$ kHz, $N = 2048$).

VI. CONCLUSIONS

The wavelet transform has been investigated and applied to analyzing sampled signal and the actual pump signal. The results of this research will be valuable asset for the analysis of vibration records and condition monitoring of machinery. The following conclusions can be drawn:

- (1) The wavelet transform is ideally suited for portraying the wide-band transient or nonstationary vibration records in time-frequency domain.
- (2) The wavelet transform has a great advantage to detect the small disturbance of the signal.
- (3) The computation time of wavelet transform is very short in comparison with other time-frequency localization techniques.
- (4) The modified Gaussian wavelet was well behavior and very effective to analyze the vibration records.
- (5) The wavelet transform characterizes the time-frequency localization of the signal well and may be useful tool for the machinery condition monitoring.
- (6) If the wavelet level, that is, frequency band, is selected at wavelet transform, its results will be a useful tool for the effective pattern recognition of machinery diagnosis and monitoring.

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APPENDIX PROGRAM LIST

A. Program List of Wavelet Transform(FORTRAN 77)

c

program wavelet

c

c

c

WAVELET TRANSFORM

c

c

by

c

c

Dept. of Mechanical Engineering

c

Naval Postgraduate School

c

c

c

c

This program is a wavelet transform by using modified
Gaussian wavelet (octave sweep or 1/3 octave sweep).

c

c

Variables

c

c

n = number of input data(n must be the power of 2.)

c

fs = sampling frequency

c

dt = sampling time(time interval)

c

bw = cutoff frequency in highpass filter

c

a = dilation

c

b = translation

c

w = coefficient of wavelet transform $|w(a,b)|^{**2}$

c

c

Array

c

c

x(i) = input data set

c

```

c      x1(i) = filtered input data set
c      bk(i) = filter weight
c
c
c      dimension x(8192),bk(4100),x1(8192)
c      complex ai,sum
c      character*16 inname,outname
c      character as
c
c      ai=cplx(0.,1.)
c      pi=atan(1.)*4.
c
c      print*, '===== '
c      print*
c      print*, '                WAVELET TRANSFORM'
c      print*
c      print*, '===== '
c      print*
c      print*, 'What is an input filename ?'
c      read(*,10) inname
c      print*, 'What is an output filename ?'
c      read(*,10) outname
10     format(a16)
c
c      select the sweep method
c
c      print*, 'What do you want the sweep method ?'
c      print*, ' if 1/1 octave, input 1'
c      print*, ' if 1/3 octave, input 2'
c      read(*,*) mswp
c
c
c      read the input data file
c
c      call indata(inname,x,fs,n,nn)
c

```

```

dt=1./fs
c
call smean(n,x)
c
print*, 'Do you want to apply highpass digital'
print*, 'filter to the original data ? (y/n)'
read(*,20) as
20 format(a1)

if (as.eq.'Y'.or.as.eq.'y') then
    print*, 'Enter the cutoff frequency of
    print*, 'the digital highpass filter (in Hz)'
    read(*,*) bw
endif

c
c signal modifications
c
c Application of highpass digital filter
c

if (as.eq.'Y'.or.as.eq.'y') then
    mo=n/2

c calculate the filter weighting

call filter(mo,bw,dt,bk)

write(*,*) 'finished filtering'

c pass the highpass filter

do 160 i=1,n
160 x1(i)=0.

do 200 i=1,n
    do 170 k=-mo,mo
        j=k

```



```

        if (k.lt.0) then
            j=k*(-1)
        endif
        j=j+1
        ll=i-k
        if (ll.lt.1) then
            ll=ll+n
        elseif (ll.gt.n) then
            ll=ll-n
        endif
        bb=-bk(j)
        if (k.eq.0) then
            bb=1-bk(j)
        endif
        x1(i)=x1(i)+bb*x(ll)
170      continue
200    continue

    do 210 i=1,n
210      x(i)=x1(i)
    endif

    if (mswp.eq.1) then
        nk=nn
        fac=1.
    elseif (mswp.eq.2) then
        nk=3*nn
        fac=3.
    endif
    nr=nk-int(fac)+1

    open(7,file=outname,status='new')
c
c    calculate wavelet transform
c
    tini=0.

```

```

ttime=dt*n
f0=2.*pi
write(7,*) tini
write(7,*) ttime
write(7,*) nn,index

do 1000 i=1,nr
    fio=2**((nk-i+1)/fac)
    a=fio*dt
    nm=int(ttime/a)
    if (nm.eq.0) nm=1
    ddt=ttime/nm
    sr=sqrt(-alog(0.01)*2)*fio
    max=int(sr)
    if (max.ge.2*n) max=2*n

    do 900 j=1,nm

        sum=cmplx(0.,0.)
        b=ddt/2.+ddt*float(j-1)
        jk=int(b/dt)+1

        do 800 k=-max,max

            t=k*dt/a
            k1=jk+k
            if (k1.lt.1) then
                if (k1.lt.-n) then
                    k1=k1+2*n
                else
                    k1=k1+n
                endif
            endif
            if (k1.gt.n) then
                if (k1.ge.2*n) then
                    k1=k1-2*n

```

```

                                else
                                    k1=k1-n
                                endif
                            endif
                            sum=sum+x(k1)*cexp(-ai*f0*t)*exp(-t*t/2.)*dt

800                                continue

                                w=cabs(sum)/sqrt(a)
                                w=abs(w)*abs(w)
                                write(7,*) i,j,w

900                                continue
1000                               continue
                                close(7)
                                stop
                                end

c
c
c
c    SUBROUTINES
c
c -----
c    subroutine indata(inname,x,fs,n,nn)

                                dimension x(*)
                                character*16 inname

c
                                open(5,file=inname,status='old')
                                read(5,*) fs,n
                                do 100 j=1,n
                                    read(5,*) t,x(j)
100                                continue
                                close(5)
                                ft=fs/2.
                                do i=1,20

```

```

        ii=2**i
        di=float(ii)
        if (di.ge.ft) then
            nn=i
            go to 200
        endif
    end do
200  continue
    return
end

c
c
    subroutine smean(n,x)
c
c    This subroutine calculates and removes the mean value of
c    the sampled data.
c
    dimension x(*)
    real meanv
c
    asum=0.
    do 100 i=1,n
        asum=asum+x(i)
100  continue
    meanv=asum/n
    do 200 i=1,n
        x(i)=x(i)-meanv
200  continue

    return
end

c
c
    subroutine filter(mo,b,t,bk)
c
c    Routine generates FIR filter weights.

```

```

c      Method devised by Potter, Bickford and Glaze.
c      There are a total of  $2M+1$  weights...filter generates  $M+1$ .
c
c      --- variables ---
c      t = the sampling interval in second.
c      b = cutoff(half-power point) of the filter in Hz;
c           must be on the range from 0 to  $1/2t$ .
c
c      Results are stored in bk
c
c      ---- Note; in the case of highpass filter, the value of
c           weight b0 must use  $1-b_0$  instead of  $b_0$ .
c
c           dimension bk(*),d(3)
c           data d0/0.35577019/,d(1)/0.2436983/,d(2)/0.07211497/,
c           * d(3)/0.00630165/
c           pi=atan(1.)*4.
c           m=m0
c      first generate plain boxcar weights
c           fact=2.*b*t
c           bk(1)=fact
c           fact=fact*pi
c           do 5 i=1,m
c               fi=i
5          bk(i+1)=sin(fact*fi)/(pi*fi)
c      trapezoidal weighting at end
c           bk(m+1)=bk(m+1)/2.
c      Now apply the Potter p310 window
c           sumg=bk(1)
c           do 15 i=1,m
c               sum=d0
c               fact=pi*float(i)/float(m)
c                   do 10 k=1,3
10                  sum=sum+2.*d(k)*cos(fact*float(k))
c               bk(i+1)=bk(i+1)*sum
15          sumg=sumg+2.*bk(i+1)

```

```
    m1=m+1
    do 20 i=1,m1
20      bk(i)=bk(i)/sumg
    return
    end
```


B. Program List of wavelet transform(MATLAB)

```
%  
%  
%           Wavelet Transform  
%  
%           by  
%           Dept. of Mechanical Engineering  
%           Naval Postgraduate School  
%  
%           Ver. 1.0      Aug. 5 1993  
%  
%           By using MATLAB Ver. 4.0  
%  
% -- Variables  
%       infile = input filename  
%       fs     = sampling frequency  
%       n      = the number of sampled dat  
%               ( n must be n-th power of 2.)  
%       avg    = mean value of sampled data  
%       fact   = the factor of sweep rate  
%       x(i)   = the magnitude of signal  
%       z(i,j) = the result of wavelet transform  
%  
%  
%       load c:\users\infile  
%       fs=infile(1,1);  
%       n=infile(1,2);  
%       dt=1/fs;  
%       x=infile(2:n+1,2);  
%       asum=0;  
%  
%  
%       remove mean value  
%  
%       for j1=1:n  
%           asum=asum+x(j1);  
%       end
```

```

    avg=asum/n;
    for i1=1:n
        x(i1)=x(i1)-avg;
    end
%
% Decide the sweep rate
%
fact=input('sweep method: 1/1 octave =1, 1/3 octave = 3 ');
%
ft=fs/2;
for i1=1:20
    ii=2^i1;
    if ii >= ft
        nn=i1;
        break
    end
end
if fact == 1
    nk=nn;
else
    nk=fact*nn;
end
nr=nk-fix(fact)+1;
%
% calculate wavelet transform
%
tini=0;
ttime=n*dt;
f0=2*pi;
jm=fix(ttime/(2*dt));
wt=zeros(nr,jm);

for i1= 1 : nr
    io=2^((nk-i1+1)/fact);
    a=io*dt;
    nm=fix(ttime/a);

```

```

if nm == 0
    nm = 1;
end
ddt=ttime/nm;
sr=sqrt(-log(0.01)*2)*io;
mx=fix(sr);
if mx >= (2*n)
    mx=2*n;
end

for j=1:nm
    sum=0+i*0;
    b=ddt/2+ddt*(j-1);
    jk=fix(b/dt)+1;
    for k=-mx:mx
        t=k*dt/a;
        k1=jk+k;
        if k1 < 1
            if k1 < -n
                k1=k1+2*n;
            else
                k1=k1+n;
            end
        end
        if k1 > n
            if k1 >= 2*n
                k1=k1-2*n;
            else
                k1=k1-n;
            end
        end
        x1=0.-i*f0*t;
        sum=sum+x(k1)*exp(x1)*exp(-t*t/2)*dt;
    end
    w=abs(sum)/sqrt(a);
    w=abs(w)*abs(w);
end

```

```

        wt(i1,j)=ww;
%
%   Plotting
%
line=128;
z=zeros(nr,line);
for i1=1:nr
    io=2^((nk-i+1)/fact);
    a=io*dt;
    k=fix(ttime/a);
    if k == 0
        k=1;
    end
    if k <= line
        step=line/k;
        k2=0;
        for ii=1:k
            k1=k2+1;
            k2=fix(step*ii);
            st=k2-k1+1;
            if st <= step
                cf=step/st;
            else
                cf=st/step;
            end

            for ij=k1:k2
                z(i1,ij)=wt(i1,ii)/cf/st;
            end
        end
    else
        step=k/line;
        k2=0;
        for ii=1:line
            k1=k2+1;
            k2=fix(step*ii);

```

```

    st=k2-k1+1;
    ssum=0;
    for ij=k1:k2
        ssum=ssum+wt(i1,ij);
    end
    if st <= step
        ssum=ssum*step/st;
    else
        ssum=ssum*st/step;
    end
    z(i1,ii)=ssum;
end
end
end
xma=max(z);
xp=max(xma)*1.2;
dt1=ttime/(line-1);
for k=1:line
    xvalue=(k-1)*dt1;
    xx(k)=xvalue;
end
for k=1:nr
    yy(k)=k;
end

surf(xx,yy,z)
xlabel('Time (sec)')
ylabel('Frequency step ')
zlabel('Amplitude')
axis([tini ttime 1 nr 0 xp])

```

C. Plotting Program List (3 Dimension)

- FOTRAN 77 and CA-DISSPLA Graphic Package -

c

program plot

c

c This program uses the graphic package CA-DISSPLA to
c plot the results of wavelet transform

c

c tmax = time record length

c tint = initial time

c fmin = start frequency step

c fmax = stop frequency step

c nn = the number of the frequency step

c fac = index of sweep method

c fname = input data filename generated by main source
c program

c

dimension rr(32768),wt(50,256)

character*25 fname

c

write(*,*) 'input file name ?'

read(*,20) fname

20

format(a25)

c

c data distribution or reduction for 3-D graphics

c

line=256

open(8,file=fname,status='old')

read(8,*) tini

read(8,*) tmax

read(8,*) nn,n,fac

nk=nn*int(fac)

nr=nk-int(fac)+1


```

ddt=tmax/n
do 1000 i=1,nr
    fio=2.**((nk-i+1)/fac)
    a=fio*ddt

k=int(tmax/a)
if (k.eq.0) k=1
if (k.le.line) then
    step=float(line)/float(k)
    k2=0
    do 950 ii=1,k
        read(8,*) i1,j1,w
        k1=k2+1
        k2=int(step*ii)
        st=float(k2-k1)+1.
        if (st.le.step) then
            coe=step/st
        else
            coe=st/step
        endif
        do 930 ij=k1,k2
            wt(i,ij)=w/coe/st
930        continue
950    continue
else
    step=float(k)/float(line)
    k2=0
    do 800 ii=1,line
        k1=k2+1
        k2=int(step*ii)
        sum=0.
        st=float(k2-k1)+1.
        do 750 ij=k1,k2
            read(8,*) i1,j1,w
            sum=sum+w
750        continue

```

```

        if (st.le.step) then
            sum=sum*step/st
        else
            sum=sum*st/step
        endif
        wt(i,ii)=sum
800      continue
        endif
1000     continue

        close(8)

        smax=0.
        do 2000 i=1,nr
            do 2000 j=1,line
                if (smax.le.wt(i,j)) smax=wt(i,j)
2000     continue
            write(*,*) 'maximum=',smax
            write(*,*) 'input the maximum scale ?'
            read(*,*) fact

            do 120 i=1,nr
                do 100 j=1,line
                    k=line*(i-1)+j
                    rr(k)=wt(i,j)
100      continue
120     continue

            dd=mod(nr,2)
            if (dd.eq.0) then
                nr=nr+1
                kk=(nr-1)*line+1
                kl=nr*line
                do 150 ip=kk,kl
150      rr(ip)=0.
            endif

```

```

c
c      plotting
c
      call pdev('ln03',ieer)
      call hwshd
      call swissm
      call shdchr(90.,1,0.002,1)
      call height(0.15)
      call physor(1.1,1.2)
      call area2d(5.5,6.75)
      call messag('WAVELET TRANSFORM $',100,1.1,8.2)
      call blsur
      call volm3d(8.,8.,9.)
      call x3name('Time (sec) $', 100)
      call y3name('Frequency step', 100)
      call z3name('Amplitude $', 100)
      call zaxang(90.)
      fmax=float(nr)
      fstep=(fmax-1)/4.
      call graf3d(tini,tmax/4.,tmax,1.,fstep,fmax,0.,'SCALE',fact)
      call surmat(rr,1,line,1,nr,1)
      call end3gr(0)
      call endpl(0)
      call donepl
      end

```

D. Plotting Program List (2 Dimension)

- FOTRAN 77 and CA-DISSPLA Graphic Package -

c

program levelplot

c

c

c

This program uses the graphic package CA-DISSPLA to
plot the results of wavelet transform with respect to each level.

c

c

tmax = time record length

c

tint = initial time

c

fmin = start frequency step

c

fmax = stop frequency step

c

nn = the number of the frequency step

c

fac = index of sweep method

c

inname = input data filename generated by main source

c

program

c

dimension x(512),y(512),wt(50,256)

character*25 inname

c

write(*,*) 'input file name ?'

read(*,20) inname

20

format(a25)

c

c

data distribution or reduction for 2-D graphics

c

line=512

open(8,file=fname,status='old')

read(8,*) tini

read(8,*) tmax

read(8,*) nn,n,fac

nk=nn*int(fac)

nr=nk-int(fac)+1

ddt=tmax/n

```

do 1000 i=1,nr
  fio=2.**((nk-i+1)/fac)
  a=fio*ddt
  k=int(tmax/a)
  if (k.eq.0) k=1
  if (k.le.line) then
    step=float(line)/float(k)
    k2=0
    do 950 ii=1,k
      read(8,*) i1,j1,w
      k1=k2+1
      k2=int(step*ii)
      st=float(k2-k1)+1.
      if (st.le.step) then
        coe=step/st
      else
        coe=st/step
      endif
      do 930 ij=k1,k2
        wt(i,ij)=w/coe/st
930      continue
950    continue
  else
    step=float(k)/float(line)
    k2=0
    do 800 ii=1,line
      k1=k2+1
      k2=int(step*ii)
      sum=0.
      st=float(k2-k1)+1.
      do 750 ij=k1,k2
        read(8,*) i1,j1,w
        sum=sum+w
750      continue
      if (st.le.step) then
        sum=sum*step/st

```

```

        else
            sum=sum*st/step
        endif
        wt(i,ii)=sum
800      continue
        endif
1000     continue

        close(8)

        smax=0.
        do 2000 i=1,nr
            do 2000 j=1,line
                if (smax.le.wt(i,j)) smax=wt(i,j)
2000     continue
            write(*,*) 'maximum=',smax
            write(*,*) 'input the maximum scale ?'
            read(*,*) smax

c
c      normalizing
c

        do 2500 i=1,nr
            do 2500 j=i,line
2500         wt(i,j)=wt(i,j)/smax

c
c      plotting
c

        call pdev('ln03',ieer)
        call hwshd
        call swissm
        call shdchr(90.,1,0.002,1)
        call height(0.15)
        call page(8.5,11.)
        call physor(1.5,1.5)
        call area2d(4.8,4.7)

```



```

call xname('Time (sec) $', 100)
call yname('Frequency step', 100)
call headin('WAVELET TRANSFORM $',100,1.1,1)
call thkfrm(0.01)
call yaxang(0.)
call graf(tini,tmax/4.,tmax,1.,1.,nr+1)
call grid(1,1)
do 3000 i=1,nr
    do 2700 j=1,line
        x(j)=dt*float(j)
        y(j)=float(i)+wt(i,j)
2700    continue

    call curve(x,y,line,0)

3000  continue

call endpl(0)
call donepl
stop
end

```


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